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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 69, PP. 241-278, 17 FIGS. MARCH 1958

GEOLOGY OF KAPINGAMARANGI ATOLL, CAROLINE ISLANDS

BY EDWIN D. MCKEE

ABSTRACT

Kapingamarangi Atoll of the Caroline Islands consists of a peripheral reef, 1000–4000 feet across, surrounding a nearly circular lagoon which is 5 by 6 nautical miles in area and about 240 feet at maximum depth. Thirty-three islands, most of which are less than half a mile in length, are scattered along the eastern half of the peripheral reef. At least 75 patch reefs, most of which are small, nearly symmetrical mounds, rise to the surface of the lagoon.

The peripheral reef and the patch reefs, composed largely of the stony structures of corals and coralline algae, have flat upper surfaces, apparently the result of bevelling by waves during a recent lowering of sea level. The islands on the peripheral reef are formed of partially consolidated stratified sediments composed of clastic limestone particles and the shells of marine animals. These islands are migrating lagoonward across the reef flat because of erosion on the seaward sides and the growth of beaches and bars on the opposite sides.

Soils on the islands are poorly developed and retain much of the texture, structure, and composition of the parent rock or sediment. They consist chiefly of mechanical mixtures of carbonaceous material and lime gravel, lime sand, or lime mud. Phosphorite is present on some islands and is still forming locally where apatite derived from bird guano is reacting with limestones.

The tidal fluctuation of ground-water lenses, determined on islands of several sizes, ranges from about 4 to 18 inches. In one very small island where the water is brackish, the rise is much greater. The time lag between tidal movements and the rise and fall of fresh water in the islands ranges from a few minutes on very small islands up to 5 hours on some large ones. This time lag is controlled by the permeability of rocks composing an island and varies from one area to another according to the distribution of rock types.

The lagoon contains six concentric belts of bottom sediment; in each, the composition and texture depend on the depth of water in which it occurs. Lime sand and lime gravel derived for the most part from the shells of animals form most of the sediment, but a lime mud covers the bottom of the deepest parts of the lagoon. Waves and currents cause gradation between types of sediment to a depth of about 30 feet, but little mixing was detected at greater depths.

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Introduction

Kapingamarangi Atoll is located at the southernmost end of the Caroline Islands, slightly more than 1° north of the Equator. It is about 410 miles southeast of Truk and 350 miles north of Rabaul in New Britain. This isolated atoll surrounds a lagoon about 6 miles across from east to west and slightly less from north to south. It is inhabited by 426 Polynesians (1954), most of whom live on Touhou and Werua Islands on the eastern side. Details of geographic setting, climate, and general environment have been treated in SIM (Scientific Investigations in Micronesia) Report No. 21 by H. J. Wiens so will not be included here.

This report on the geology of Kapingamarangi Atoll covers preliminary results from field investigations conducted during June, July, and August of 1954 and laboratory examination of specimens made during 1954–1955. Detailed studies, involving the classification of sediments and sedimentary rocks, the occurrence and behavior of ground water, and the distribution of soils on the islands were made. On the reef and in the lagoon, investigation of the processes of sedimentation was undertaken. These studies included analyses of beach and bar structures, reconstruction of reef and offshore profiles, and systematic sampling of the lagoon floor.

Terminology used in this report follows Tracey *et al.* (1955). The term "atoll" is used for the peripheral reef and everything within it. The upper surface of the peripheral reef, except where covered by islands, is referred to as the reef flat. Small reefs within the lagoon, variously referred to as patch reefs, small table reefs, reef knolls, and reef pinnacles, are discussed under the designation of patch reef. Dense growths of staghorn or branching corals are referred to as thickets.

Acknowledgments

This geological investigation was part of a project of the Pacific Science Board of the National Research Council and was supported by funds from the Office of Naval Research through contract with the National Academy of Sciences. The U. S. Navy Department and the Military Air Transport Service furnished transportation to and from the atoll, and the Navy Department supplied much equipment. The Civil Administrative staff of the Trust Territory of the Pacific Islands was helpful.

Harold Coolidge, Lenore Smith, and the late Ernestine Akers of the Pacific Science Board helped greatly in organization and planning. Kenneth P. Emory of the Bishop Museum in Honolulu supplied information on the atoll and introduced us to its people. Preston Cloud

and Joshua Tracey of the U. S. Geological Survey made suggestions and generously loaned scientific equipment.

Associates in the field party were Cadet Hand, Robert R. Harry, W. Jan Newhouse, William Niering, and H. J. Wiens, all of whom contributed to the development of this report. Wiens prepared base maps of the islands that were of great value in recording geologic data; Niering assisted in making soil studies and tide recordings. Kapingans who served faithfully as assistants throughout the summer were Taitos, interpreter, and Aisea, Exsol, and Turibureti, boatmen and test-pit diggers.

In the study of collections and samples of materials, I have been assisted by the following specialists:

John W. Wells, Cornell University, Coral identification.

Ruth Todd, U. S. Geological Survey, Foraminifera identification.

John Hem, U. S. Geological Survey, Analyses of water from wells and lagoon.

A. J. Gude III, U. S. Geological Survey, X-ray diffraction identification of minerals.

P. B. Barnett, U. S. Geological Survey, Analyses of elements in soils.

For critical reading of the manuscript and many helpful suggestions, the writer is indebted to G. D. Robinson of the U. S. Geological Survey, John Chronic of the University of Colorado, and Halka P. Chronic.

Atoll Framework

The peripheral reef of Kapingamarangi Atoll (Fig. 1) almost encloses an oval lagoon. The only major breaks are two narrow passes on the south side where strong currents flow in and out continuously through channels nearly 20 feet deep. This peripheral reef includes the "frame" of the reef complex or reef mass and is a lattice constructed by organisms, especially corals and coralline algae. These organisms as noted by Cloud (1952a, p. 2128) "serve to hold it (the reef) together, and the frame they build is a trap for clastic or chemically precipitated sediments."

The surface of the peripheral reef is nearly 4000 feet wide in the north and west (Fig. 1). Along the southern arc, west of the passes, the surface is only 1000 feet wide. The 33 islands distributed along the eastern half of the reef appear as low mounds slightly above the flat top along its lagoonward margin. They alone stand above high-tide waters. Elsewhere along the atoll, especially on the southwestern, western, and northwestern sectors, the reef surface is divided into a seaward slope and a lagoonward slope by a low crest. Both slopes are extremely gentle in most places. They are referred to in this paper as the outer-reef flat and the inner-reef flat.

The flat top of nearly all the outer part and some of the inner part of the reef forms a pitted rock pavement. Over wide areas this surface does not contain any organisms which are contributing appreciably to growth of the reef at present. It seems to be the result of the wearing down, by waves and currents, of coral masses. Evidence from Okinawa (MacNeil, 1950) indicates that similar surfaces there are the result of recent wave or solution planation. Comparable reef flats reported by various geologists on other islands of the Pacific suggest that this widespread feature is the effect of a recent lowering of sea level with resultant death of all corals back from the reef edge, followed by a bevelling of higher parts of the reef structure.

The present evenly planed and nearly sterile reef surface probably results from an essentially static position of sea level during a considerable period. At present, small living algae of the genus *Boodlea* cover much of the rock surface; mollusks and other marine animals congregate around and under limestone boulders and coral heads (debris washed across from the seaward side) that are strewn over the rock surface. Brittle stars, eels, and marine worms inhabit cracks and cavities in the rock mass. Living corals and coralline algae, however, are restricted for the most part to the seaward margins of the reef and, on the western side where islands are absent, to waters of the inner reef area bordering the lagoon edge.

Clastic sediments are scarce over much of the present reef-flat surface but are progressively more abundant toward the inner margins of the reef where they veneer the coral framework. The small amount of fragmental material on the outer side of the reef flat consists largely of coral and coralline algal debris up to boulder size strewn over the surface, and of clastic particles from mollusk shells and echinoid spines which are concentrated in pockets and cracks. Foraminifera of the genus *Calcarina* that are common on the reef flats of many Pacific atolls are absent here; few Foraminifera of any type occur on the seaward parts of the atoll. The tests of these animals accumulate in quantities sufficient to form deposits of lime sand only on the island lagoon beaches and on the inner parts of the atoll. Such lime sands,

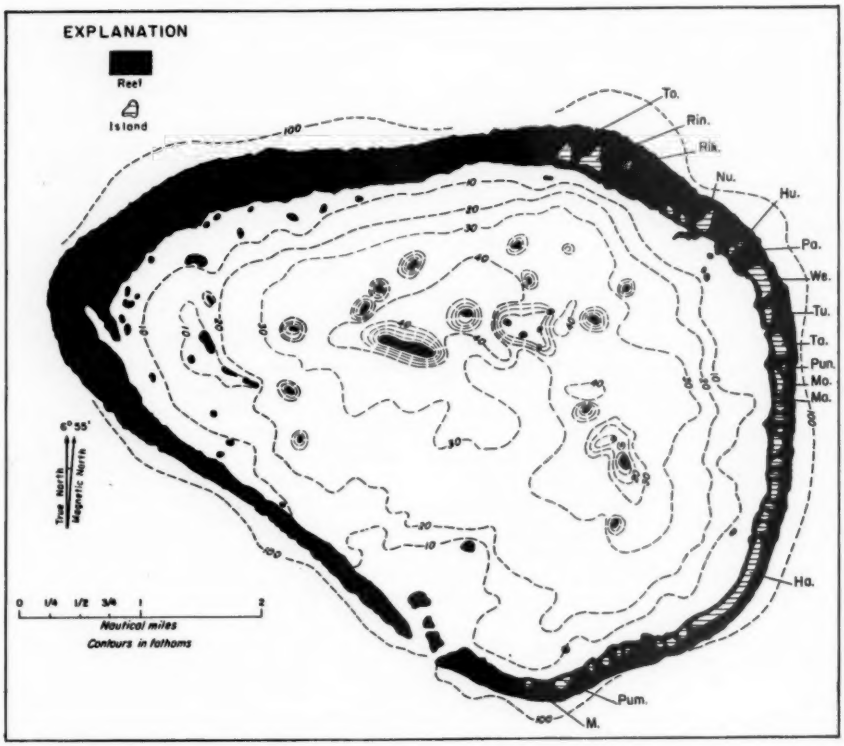

FIGURE 1.—KAPINGAMARANGI ATOLL SHOWING LOCATION OF ISLANDS AND REEFS

Isobathic Lines in Lagoon Compiled from Data on U. S. Navy Hydrographic Office Chart 6042.

To.—Torongahai Island
Rin.—Ringutoru
Rik.—Rikumanu
Nu.—Nunakita
Hu.—Hukuniu
Pa.—Parakahi
We.—Werua
Tu.—Touhou
Ta.—Taringa
Pun.—Pungupungu
Mo.—Matiro
Ma.—Matuketuke
Ha.—Hare
Pum.—Pumatahati
M.—Matukerekere

however, ultimately fill many of the interstices in the framework limestone as noted by Sollas (1904, p. 6, 27), and they develop into extensive deposits on the inner side of the "retaining wall" of coral and algal structures.

Studies were made of material exposed in cracks below the pavement and of large boulders washed up from seaward exposures. The investigation was hampered by the extreme difficulty of digging into the reef rock and by a lack of naturally exposed sections, but from a series of samples some generalizations can be made. Although in many specimens the reef rock is aphanitic, in others the relict structures of corals are clearly preserved.

The framework limestone as a whole is cavernous, although many small specimens have a relatively low porosity. Cavernous structure, observed in near-surface excavations, probably extends to considerable depths, as indicated by the fresh-water lenses on various islands that rise simultaneously and with a similar tidal lag (described under Ground Water). It is also suggested by evidence from the drill holes at Funafuti (Sollas, 1904, p. 6) and at Eniwetok Atoll (Ladd *et al.*, 1953, p. 2259). On the other hand, some cavities appear to have filled with clastic sediment. This feature was also noted by Newell (1954, p. 18) in reef blocks from the outer edge of the reef flat at Raroia.

The reef-building organisms that contribute to the framework limestone, as indicated by the forms currently growing along the eastern

seaward margin of the atoll, are predominantly corals with some masses of the coralline alga *Porolithon onkodes*. The corals are represented by many species. The most common corals belong to the genus *Acropora*, except along the inner margin, where micro-atolls of *Porites lutea* are dominant. X-ray diffraction studies of selected limestone samples suggest that much of the rock beneath the present reef flat was formed from comparable assemblages.[1] All specimens show at least 90 per cent aragonite, which probably reflects the proportion of coral, although a small amount of aragonite may be due to interstitial deposits of clastic shells. The amount of algal contributions is indicated by the relatively high (5–10 per cent) amount of magnesium carbonate. Chave (1954, p. 267) noted that in mollusks and certain other organisms the amount of magnesium carbonate in the calcite is less than 2 per cent; in algal structures it is more than 10 per cent. A lack of normal calcite in all samples indicates that the common reef-dwelling Foraminifera of the genus *Amphistegina* were not included in the samples examined.

Data are not yet available on the lithology or structure of the Kapingamarangi reef at appreciable depths below the pavement of the reef flat. Well records from other atolls (Fairbridge, 1950, p. 384), however, suggest that zones of clastic materials representative of various depths and environments alternate with zones of reef-forming corals and algae similar to those on the surface today. Such changes at depth are probably related to advance and retreat of the actively growing framework corals and coralline algae and probably were controlled by relative changes of sea level and stillstands. Both the upward and the lateral development of the limestone framework record tetonic and climatic events.

Geology of the Islands

Character of the Islands

Thirty-three islands are distributed along the arc that forms the eastern, windward peripheral reef of Kapingamarangi Atoll. Hare Island, the largest, is more than a mile long and 600 feet wide; Matukerekere Island, the smallest, is about 130 feet long. Some of these islands are composite, having attained their present size from the combining of two or more small islands by sedimentation; others probably represent various stages of diminution through partial destruction or dissection by cyclonic storms.

Man has speculated for a long time about the origin of islands which are perched on oceanic atolls. Some early views on this subject are recorded in Captain Cook's log (Lloyd, 1949, p. 266) of April 17, 1777:

> "There are different opinions amongst ingenious theorists, concerning the formation of such low islands as Palmerston's. Some will have it, that, in remote times, these little separate heads or islets were joined and formed one continued and more elevated tract of land, which the sea, in the revolution of ages, has washed away, leaving only the higher grounds; which, in time, also, will, according to this theory, share the same fate. Another conjecture is, that they have been thrown up by earthquakes, and are the effect of internal convulsions of the globe. A third opinion, and which appears to me as the most probable one, maintains that they are formed from shoals, or coral banks, and of consequence increasing."

Geologic maps were prepared during the summer of 1954 for all the larger and some of the smaller islands on Kapingamarangi Atoll (Fig. 2). Island maps (1 inch equals 100 feet), compiled and surveyed by H. J. Wiens, furnished bases. The distribution of sedimentary materials was plotted according to the classification discussed in the section on Petrology. Primary dips in strata were recorded on the maps.

Kapingamarangi islands are formed of three classes of material: (1) sedimentary rocks formed by cementation of clastic particles and organic remains; (2) unconsolidated sediments of beaches and bars; and (3) surficial deposits forming the ramparts, rampart wash, and soils (not mapped) that partly cover and mask the other two. The distribution and structure of these three classes of material are a key to much of the island history.

Sedimentary Rocks

Beds of sedimentary rock rise above the reef flats along the seaward margins of all the large islands and many of the small ones and crop out locally within many islands. Because in most places their clastic particles are clearly discernible and because their stratification commonly is prominent after weathering, these rocks, for the most part, are readily distinguishable from the reef rock on which they rest. Isolated pedestals and undercut blocks of similar clastic rock stand on the reef flat considerable distances seaward from some islands; these represent the remnants of earlier

[1] Analyses by A. J. Gude III, U. S. Geological Survey.

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Soils on the islands are poorly developed and retain much of the texture, structure, and composition of the parent rock or sediment. They consist chiefly of mechanical mixtures of carbonaceous material and lime gravel, lime sand, or lime mud. Phosphorite is present on some islands and is still forming locally where apatite derived from bird guano is reacting with limestones.

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Atoll Framework

The peripheral reef of Kapingamarangi Atoll (Fig. 1) almost encloses an oval lagoon. The only major breaks are two narrow passes on the south side where strong currents flow in and out continuously through channels nearly 20 feet deep. This peripheral reef includes the "frame" of the reef complex or reef mass and is a lattice constructed by organisms, especially corals and coralline algae. These organisms as noted by Cloud (1952a, p. 2128) "serve to hold it (the reef) together, and the frame they build is a trap for clastic or chemically precipitated sediments."

The surface of the peripheral reef is nearly 4000 feet wide in the north and west (Fig. 1). Along the southern arc, west of the passes, the surface is only 1000 feet wide. The 33 islands distributed along the eastern half of the reef appear as low mounds slightly above the flat top along its lagoonward margin. They alone stand above high-tide waters. Elsewhere along the atoll, especially on the southwestern, western, and northwestern sectors, the reef surface is divided into a seaward slope and a lagoonward slope by a low crest. Both slopes are extremely gentle in most places. They are referred to in this paper as the outer-reef flat and the inner-reef flat.

The flat top of nearly all the outer part and some of the inner part of the reef forms a pitted rock pavement. Over wide areas this surface does not contain any organisms which are contributing appreciably to growth of the reef at present. It seems to be the result of the wearing down, by waves and currents, of coral masses. Evidence from Okinawa (MacNeil, 1950) indicates that similar surfaces there are the result of recent wave or solution planation. Comparable reef flats reported by various geologists on other islands of the Pacific suggest that this widespread feature is the effect of a recent lowering of sea level with resultant death of all corals back from the reef edge, followed by a bevelling of higher parts of the reef structure.

The present evenly planed and nearly sterile reef surface probably results from an essentially static position of sea level during a considerable period. At present, small living algae of the genus *Boodlea* cover much of the rock surface; mollusks and other marine animals congregate around and under limestone boulders and coral heads (debris washed across from the seaward side) that are strewn over the rock surface. Brittle stars, eels, and marine worms inhabit cracks and cavities in the rock mass. Living corals and coralline algae, however, are restricted for the most part to the seaward margins of the reef and, on the western side where islands are absent, to waters of the inner reef area bordering the lagoon edge.

Clastic sediments are scarce over much of the present reef-flat surface but are progressively more abundant toward the inner margins of the reef where they veneer the coral framework. The small amount of fragmental material on the outer side of the reef flat consists largely of coral and coralline algal debris up to boulder size strewn over the surface, and of clastic particles from mollusk shells and echinoid spines which are concentrated in pockets and cracks. Foraminifera of the genus *Calcarina* that are common on the reef flats of many Pacific atolls are absent here; few Foraminifera of any type occur on the seaward parts of the atoll. The tests of these animals accumulate in quantities sufficient to form deposits of lime sand only on the island lagoon beaches and on the inner parts of the atoll. Such lime sands,

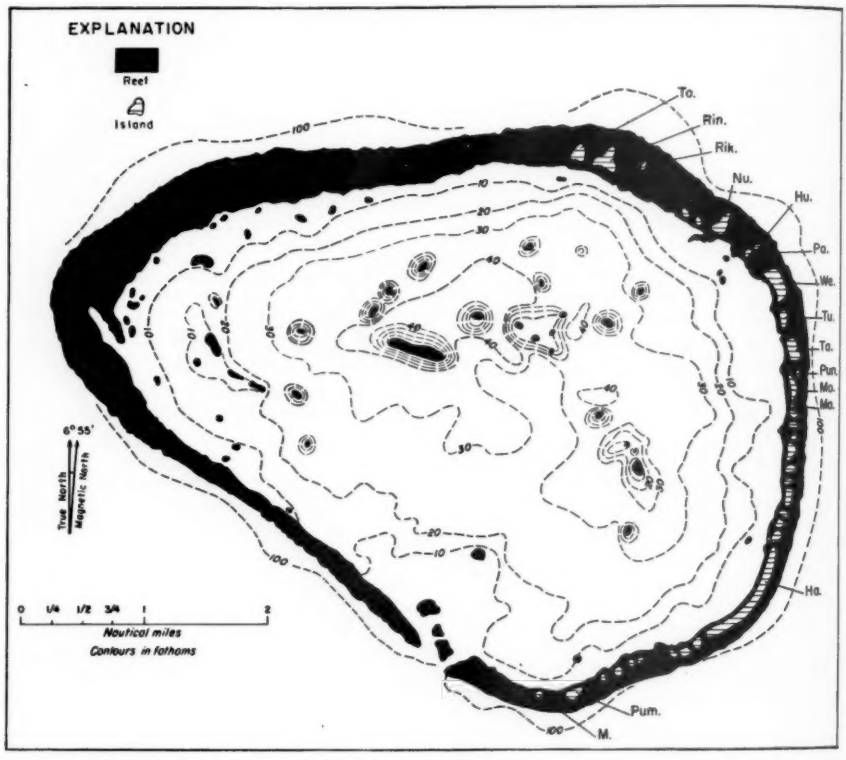

FIGURE 1.—KAPINGAMARANGI ATOLL SHOWING LOCATION OF ISLANDS AND REEFS

Isobathic Lines in Lagoon Compiled from Data on U. S. Navy Hydrographic Office Chart 6042.

To.—Torongahai Island	Pa.—Parakahi	Mo.—Matiro
Rin.—Ringutoru	We.—Werua	Ma.—Matuketuke
Rik.—Rikumanu	Tu.—Touhou	Ha.—Hare
Nu.—Nunakita	Ta.—Taringa	Pum.—Pumatahati
Hu.—Hukuniu	Pun.—Pungupungu	M.—Matukerekere

however, ultimately fill many of the interstices in the framework limestone as noted by Sollas (1904, p. 6, 27), and they develop into extensive deposits on the inner side of the "retaining wall" of coral and algal structures.

Studies were made of material exposed in cracks below the pavement and of large boulders washed up from seaward exposures. The investigation was hampered by the extreme difficulty of digging into the reef rock and by a lack of naturally exposed sections, but from a series of samples some generalizations can be made. Although in many specimens the reef rock is aphanitic, in others the relict structures of corals are clearly preserved.

The framework limestone as a whole is cavernous, although many small specimens have a relatively low porosity. Cavernous structure, observed in near-surface excavations, probably extends to considerable depths, as indicated by the fresh-water lenses on various islands that rise simultaneously and with a similar tidal lag (described under Ground Water). It is also suggested by evidence from the drill holes at Funafuti (Sollas, 1904, p. 6) and at Eniwetok Atoll (Ladd *et al.*, 1953, p. 2259). On the other hand, some cavities appear to have filled with clastic sediment. This feature was also noted by Newell (1954, p. 18) in reef blocks from the outer edge of the reef flat at Raroia.

The reef-building organisms that contribute to the framework limestone, as indicated by the forms currently growing along the eastern

seaward margin of the atoll, are predominantly corals with some masses of the coralline alga *Porolithon onkodes*. The corals are represented by many species. The most common corals belong to the genus *Acropora*, except along the inner margin, where micro-atolls of *Porites lutea* are dominant. X-ray diffraction studies of selected limestone samples suggest that much of the rock beneath the present reef flat was formed from comparable assemblages.[1] All specimens show at least 90 per cent aragonite, which probably reflects the proportion of coral, although a small amount of aragonite may be due to interstitial deposits of clastic shells. The amount of algal contributions is indicated by the relatively high (5–10 per cent) amount of magnesium carbonate. Chave (1954, p. 267) noted that in mollusks and certain other organisms the amount of magnesium carbonate in the calcite is less than 2 per cent; in algal structures it is more than 10 per cent. A lack of normal calcite in all samples indicates that the common reef-dwelling Foraminifera of the genus *Amphistegina* were not included in the samples examined.

Data are not yet available on the lithology or structure of the Kapingamarangi reef at appreciable depths below the pavement of the reef flat. Well records from other atolls (Fairbridge, 1950, p. 384), however, suggest that zones of clastic materials representative of various depths and environments alternate with zones of reef-forming corals and algae similar to those on the surface today. Such changes at depth are probably related to advance and retreat of the actively growing framework corals and coralline algae and probably were controlled by relative changes of sea level and stillstands. Both the upward and the lateral development of the limestone framework record tetonic and climatic events.

Geology of the Islands

Character of the Islands

Thirty-three islands are distributed along the arc that forms the eastern, windward peripheral reef of Kapingamarangi Atoll. Hare Island, the largest, is more than a mile long and 600 feet wide; Matukerekere Island, the smallest, is about 130 feet long. Some of these islands are composite, having attained their present size from the combining of two or more small islands by sedimentation; others probably represent various stages of diminution through partial destruction or dissection by cyclonic storms.

Man has speculated for a long time about the origin of islands which are perched on oceanic atolls. Some early views on this subject are recorded in Captain Cook's log (Lloyd, 1949, p. 266) of April 17, 1777:

> "There are different opinions amongst ingenious theorists, concerning the formation of such low islands as Palmerston's. Some will have it, that, in remote times, these little separate heads or islets were joined and formed one continued and more elevated tract of land, which the sea, in the revolution of ages, has washed away, leaving only the higher grounds; which, in time, also, will, according to this theory, share the same fate. Another conjecture is, that they have been thrown up by earthquakes, and are the effect of internal convulsions of the globe. A third opinion, and which appears to me as the most probable one, maintains that they are formed from shoals, or coral banks, and of consequence increasing."

Geologic maps were prepared during the summer of 1954 for all the larger and some of the smaller islands on Kapingamarangi Atoll (Fig. 2). Island maps (1 inch equals 100 feet), compiled and surveyed by H. J. Wiens, furnished bases. The distribution of sedimentary materials was plotted according to the classification discussed in the section on Petrology. Primary dips in strata were recorded on the maps.

Kapingamarangi islands are formed of three classes of material: (1) sedimentary rocks formed by cementation of clastic particles and organic remains; (2) unconsolidated sediments of beaches and bars; and (3) surficial deposits forming the ramparts, rampart wash, and soils (not mapped) that partly cover and mask the other two. The distribution and structure of these three classes of material are a key to much of the island history.

Sedimentary Rocks

Beds of sedimentary rock rise above the reef flats along the seaward margins of all the large islands and many of the small ones and crop out locally within many islands. Because in most places their clastic particles are clearly discernible and because their stratification commonly is prominent after weathering, these rocks, for the most part, are readily distinguishable from the reef rock on which they rest. Isolated pedestals and undercut blocks of similar clastic rock stand on the reef flat considerable distances seaward from some islands; these represent the remnants of earlier

[1] Analyses by A. J. Gude III, U. S. Geological Survey.

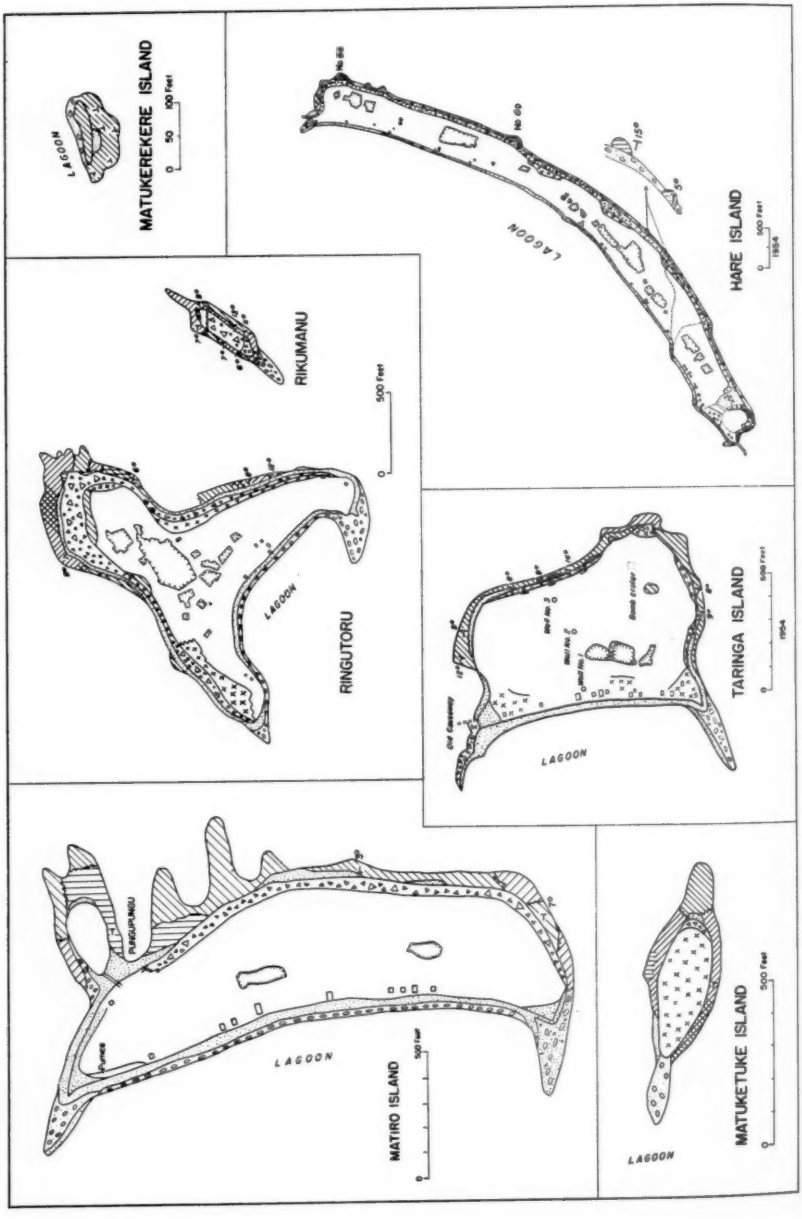
MATUKEREKERE ISLAND
LAGOON
0 50 100 Feet
HARE ISLAND
LAGOON
No. 60
No. 59
500 Feet
1954
RIKUMANU
RINGUTORU
LAGOON
500 Feet
TARINGA ISLAND
LAGOON
500 Feet
1954
MATIRO ISLAND
TUNGUPUNGU
LAGOON
500 Feet
MATUKETUKE ISLAND
LAGOON
500 Feet

FIG. 2a

FIG. 2a

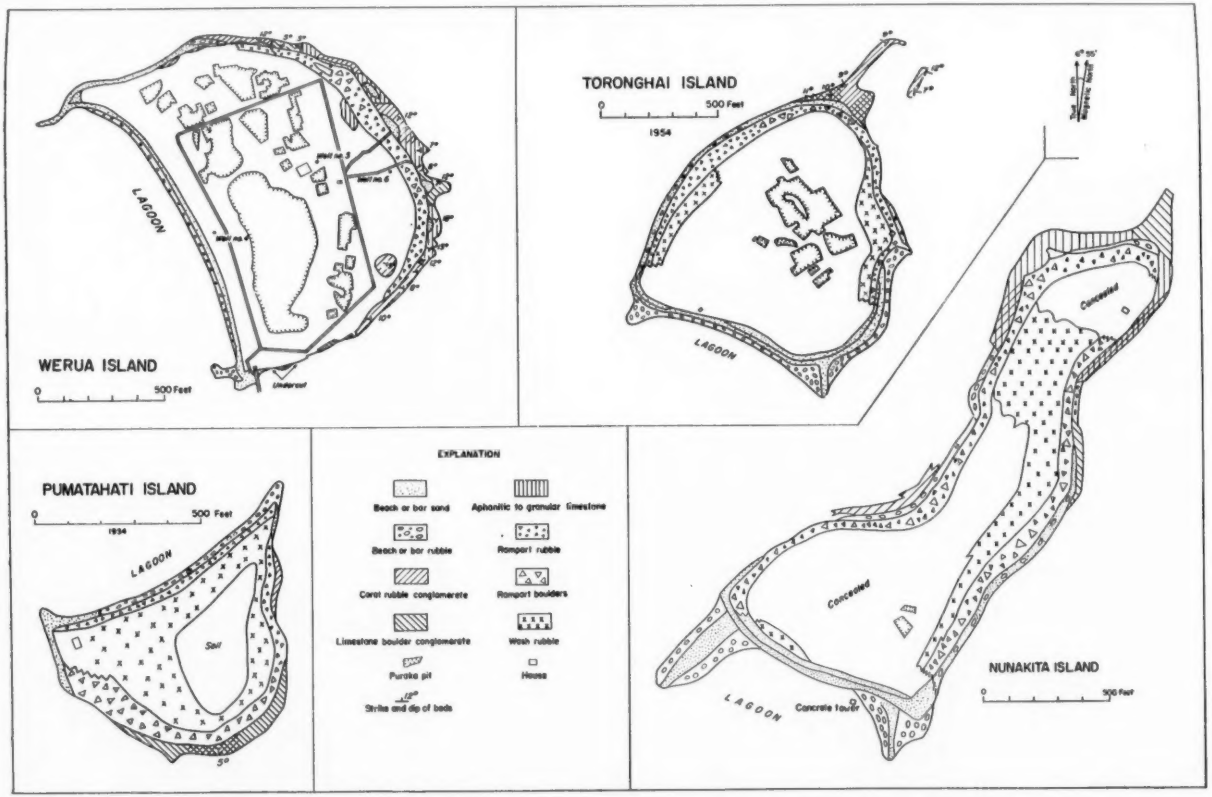

FIGURE 2.—GEOLOGIC MAPS OF THE ISLANDS OF KAPINGAMARANGI ATOLL

island masses. Conspicuous examples are on the flats east of Werua Island. Furthermore, relict platforms of stratified clastic rock, worn to a low level through planation but standing above the coral rock of the reef flat, extend 400 feet northeastward from Torongahai Island.

presence of apatite in coastal stratified rock Nunakita and Ringutoru Islands in wave-washed areas beyond the present limits of trees. This distribution indicates that phosphorite must have developed when these localities were the interiors of islands and when guano from birds was accumulating nearby.

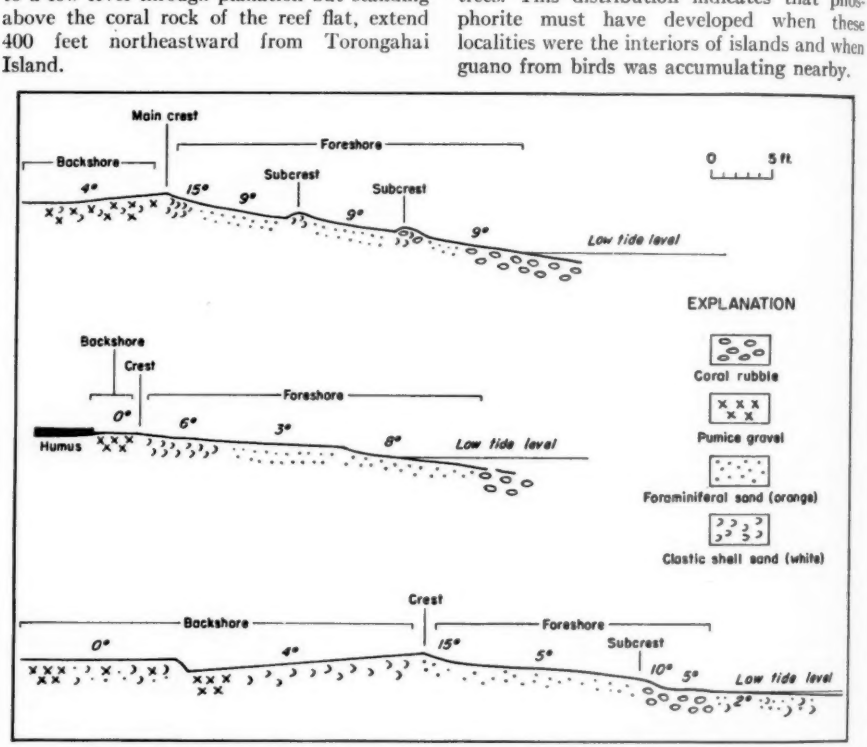

FIGURE 3.—PROFILES OF LAGOON BEACHES AND DISTRIBUTION OF BEACH SEDIMENT

The distribution of erosional remnants of stratified rock suggests that the seaward shores of all Kapingamarangi islands have been retreating as a result of wave activity for a considerable time. Similar evidence on Raroia, indicating reef-flat extension at the expense of the islands, has been noted by Newell (1954, p. 14). This concept is supported by the orientation of cross-stratification along shore-line exposures of island rock. On many islands, of which Werua (Fig. 2) is an excellent illustration, rock strata along the seaward coast dip lagoonward over long stretches in the same manner and degree as strata in the modern lagoon beaches. This suggests that strata in the two places developed in a similar manner and therefore, that the deposits forming the rocks accumulated when the lagoon margin was in the present position of the seaward shore. Still further evidence of island retreat is the

The present distribution of stratified rock indicates not only a former more seaward position of the islands but also a higher surface level. Cross-stratified rocks on various islands, especially prominent on Rikumanu and Ringutoru, stand 4–5 feet above the present high-tide level. These rocks are formed of clastic particles; they appear to be leached and partly phosphatized. Rocks having a similar high-level position have been recorded in many atolls of the Pacific (David and Sweet, 1904, p. 67–68; Ladd *et al.*, 1950, p. 413) and are thought to have been deposited when, owing to eustatic changes, sea level was higher than at present.

Lagoon Beaches and Bars

Large parts of most of the islands, including nearly all of the lagoonward sides, are today

composed of unconsolidated clastic materials and foraminiferal sands. Such sediments are accumulating on the bars or horns projecting into the lagoon from both ends of each island and along the incurving beaches between these bars (Fig. 2). Test pits and wells on several islands indicate that similar unconsolidated materials extend downward in many places at least as far as low-water level, 3–4 feet below the surface. Sedimentary structures, especially stratification, show that these sediments were deposited as beaches, dipping lagoonward, and as bars.

Beaches and bars on all the major islands were mapped, and details of structure were recorded from trenches dug at right angles to the strand on Taringa, Parakahi, Matiro, Pumatahita, and Ringutoru islands. These studies are incomplete, but some salient features are shown on three typical beach profiles (Fig. 3). The foreset beds of the beaches dip 4°-11° lagoonward, except immediately below below beach crests, where many dip as much as 15°–20° (Table 1). Strata on back-shore beaches commonly are horizontal, but some dip inland 3°–4°. There is no evidence that any lagoon beaches are being converted into beach rock; beach deposits encountered in test holes on the lagoon sides of islands were unconsolidated.

Lagoon beach deposits vary in composition according to wave conditions. Their principal components normally are sufficiently well sorted to form distinctive parallel bands along the beach. These bands are concentrations of: (1) lime sand composed largely of an orange, ovoid foraminifer (*Amphistegina madagascariensis*), with lesser amounts of a white, disc-shaped foraminifer (*Marginopora vertebralis*); (2) white coquina sand composed for the most part of comminuted pieces of shell; (3) worn gray coral rubble up to 1½-2 inches long; (4) pieces of gray or black pumice averaging from a quarter to half an inch in diameter but ranging up to 5 inches; all specimens are worn and rounded except where freshly broken along fractures.

Pumice is concentrated on the back shore as a result of the sorting of beach materials according to weight and specific gravity; the other three types of sediment are deposited on foreshore beaches. The orange foraminiferal sands dominate the foreshore surfaces of most lagoon beaches at present, but on Pumatahati and parts of Hare Island coral rubble covers the surface because orientation of these beaches is such that they are exposed to strong wave action. Test trenches show that at times all the beaches have been covered by deposits of rubble, but most of these beaches were later buried by sand as they extended forward under conditions of normal wave action. Island horns or bars that are now building out into the lagoon consist of foraminiferal sand and coral rubble; the distribution of each material depends on conditions of local current and wave strength.

TABLE 1.—CHARACTERISTICS OF LAGOON BEACHES

Island	Width, low tide (feet)	Angle of dip toward lagoon (degrees)		
		Foreshore slope	Subcrest slope	Backshore slope
Taringa	23	5–11	.....	...
Parakahi	23	5–10	15	...
Matiro	15	7	16	...
Pumatahati	20	4–9	(Rampart 29)	...
Ringutoru	26	9	15	0–4
Torongahai	..	8	20	0–2

Unconsolidated beach and bar deposits that form major parts of some islands on Kapingamarangi indicate that sedimentation has built the lagoonward sides of these islands forward at an appreciable but undetermined rate. Beach trenches show the recent accumulation of back-shore deposits over foreshore sediments; test pits near the shore expose humus layers mixing with back-shore deposits; wells in the interior show sequences of lagoonward-dipping foraminiferal sands of former beaches. The relict zones of pumice, located back from the margins of some beaches and marking the back-shore accumulations of earlier periods are the most conspicuous indicators of beach migration. Similar bands of pumice are reported by Sewell (1936, p. 77) on Addu Atoll.

Whether this aggradational process corresponds to the rate of island destruction on the seaward side is not known. Presumably during the current stillstand of the sea the rate of wearing back of land has decreased in proportion to the distance from the reef front. Although the present reef flat is relatively wide in most places, erosive forces of the sea are still effective on many of the islands. On the other hand, the rate of island building through sedimentation may be retarded, for the shore moves forward into continually greater depths of the lagoon, requiring greater amounts of sediment to build up the bottom.

Seaward Beaches

Beaches are relatively scarce on the seaward sides of Kapingamarangi islands; where they do occur they are small and short-lived. Most of them are perched on the bevelled surfaces of stratified island rock above low-tide level as indicated on the geologic maps (Fig. 2). It is doubtful that any of these beaches make permanent contributions to the growth of the islands.

The seaward beaches differ from the beaches on the lagoon sides of islands not only in being less extensive, but also in composition and color. They consist of comminuted white mollusk shells, in contrast to the orange foraminiferal lagoon beaches. A small beach at the seaward end of Pungupungu Island (Fig. 2) forms a coquina composed almost entirely of unbroken shells of a small pelecypod of the genus *Trigonocardia*.

Ramparts and Rampart Wash

Occasional violent storms deposit coral rubble, coral heads, and limestone blocks on the borders of most islands above wave-cut benches and beach crests. The deposits are classified as boulder ramparts and rubble ramparts or as rampart wash if the debris has been spread out as a sheet below and beyond the inland part of the rampart ridge.

Present distribution of these surficial deposits (Fig. 2) indicates the directions of approach and the intensities of recent storms. Large islands along the northern arc of the atoll (Torongahai, Ringutoru, and Nunakita) all have large ramparts on both eastern and western shores. The widest are on the western sides, and in these the largest blocks (36 inches in diameter on Torongahai) are concentrated near the northern ends (Table 2).

Islands of the eastern arc (Werua, Matiro, and Hare) have ramparts on their seaward sides, but these ramparts are formed mostly of fine rubble with small areas of boulders. Individual blocks are much smaller than on northern islands (Table 2). On the southern arc, at Pumatahati Island, large ramparts have been formed on both seaward and lagoonward shores. The seaward rampart consists largely of boulders; the lagoon rampart consists of coral rubble only. The unique development of a lagoon-facing rampart on this island must be attributed to a fetch sufficiently great to allow easterly storms in the lagoon to reach high intensity.

Rampart wash (Fig. 2) extends inland from the ramparts as much as 250 feet, forming a coral-rubble surface. Because rampart wash has developed largely on the seaward sides of islands, it rests on bedrock in many places and on soil in others. Apparently waters wash some of the small gravels and other constituents of the rampart beyond its crest. On the northern island, especially, rampart wash covers large areas extending inland from the seaward margins.

Migration of Islands

The seaward sides of islands are currently being eroded back so that the outer reef flat is becoming wider at the expense of stratified island rock, and the lagoon sides of islands are growing through accumulation and deposition of beach and bar sediments. This results in island migration across the reef, from seaward to lagoonward side. As long as sea level remains relatively stable this process may continue even though increasing distance from the reef front decreases the effective cutting power of waves, and the advance of the lagoon shore into progressively deeper waters requires more sedimentary material to build up a comparable beach front. J. I. Tracey (Written communication, July 1955) suggests that solution is more effective than abrasion by waves in the retreat of islands and that wide reefs favor rapid solution. He also suggests that wide reefs may favor rapid sedimentation as they probably provide more sediment. Thus, it is not known whether or not these islands migrate at a progressively slower rate.

Many biological features support the thesis of island migration. Trees, especially coconut palms, are undermined by waves on the seaward shores. Many such trees are tilted or have fallen outward from the island margins. The Kapingans are aware of the effectiveness of this process and on both Touhou and Werua have constructed stone embankments along the southeast coasts to protect the land. Recent growth of lagoon shores is illustrated on several islands where successive lines of certain shore-fringing species of trees, now standing in the interiors, mark the sites of former shore lines. The relationships of island migration to plant life have been studied by Niering (1956).

On Kapingamarangi Atoll, island migration apparently has been greatest in the northern islands and least in the southern. This is indicated by a wider outer reef flat in the north than in the south and by the extent of bevelled

remnants of stratified bedrock outward from the seaward coasts of Torongahai, Ringutoru, Nunakita, and Werua islands (Fig. 2). In contrast, Hare Island, on the southern part of the atoll, appears to have been relatively some being extremely friable, some well cemented and dense. Much of it is stratified or cross-stratified, and it has all the characteristics attributed to beachrock. Its origin is not entirely clear, however, despite numerous

TABLE 2.—DISTRIBUTION OF RAMPARTS AND RAMPART WASH

	Island	Boulder rampart			Rubble rampart		Rampart wash	
		Location	Width (feet)	Size of boulders (inches)	Location	Width (feet)	Location	Width (feet)
Northern	Torongahai	West shore	47–72	36	South part of east and west shores	..	Blanket bordering rampart	15–92
		East shore	28–32	12				
	Ringutoru	North shore	115–164	24	Part of west shore	..	Southwest end borders east rampart	30–200
		West shore	18–77	6–10				23–72
		East shore	21–54	6–12				
	Rikumanu	Entire surface	100	18–24	.....	..	.....	..
	Nunakita	West shore	22–100	12–36	South part of east and west shores	..	North end borders east rampart	250
		East shore	31–68	6–8				32–96
Eastern	Werua	Southeast shore	57–120	24	South shore	36–60	Borders east rampart	..
					East shore	75–100		
	Matiro	Southeast shore, small area	..	6–24	East shore	16–40	.....	..
	Matuketuke	East end	32	6–24	.....	..	Entire surface	150
	Hare	Northeast shore	42–67	6–12	East shore	31–100	Borders east rampart	33–85
					Southeast shore	36–45		
Southern	Pumatahati	South shore	33–100	6–12	North shore	15–20	West end borders rampart	250
								30–100

stable; it shows little shore recession on the seaward side and is not building out lagoonward rapidly. Its adjacent outer reef flat is comparatively narrow. Its lagoon beach is probably similar to that at Arno Atoll described by Wells (1951, p. 5) as "degrading." Much of the Arno Atoll surface likewise is covered by rubble concentrates, and several coconut palms near it are partly undermined.

Problem of Kapingamarangi Beachrock

Most of the rock forming the islands of Kapingamarangi Atoll is composed of calcareous skeletal debris and rock fragments, cemented by calcium carbonate. It varies greatly in texture and in degree of cementation, published suggestions concerning the origin of beachrock.

Because modern beachrock is limited to tropical seas, its relationship to warm waters seems to be beyond question. Because it develops exclusively in the intertidal zone, its relationship to the rise and fall of tides seems equally definite. The factors responsible for its localization on certain beaches or parts of beaches are less clear. Conditions controlling its development as postulated by Ginsburg (1953, p. 88) are: (1) high temperature, (2) rapid rate of beach drainage between high tides, and (3) a permanence of beach deposits sufficient to allow cementation. The localization of beachrock is commonly attributed to the precipitation of calcium carbonate from sea water as a

result of heating and evaporation. The probable importance of blue-green algae as agents that bind sand grains together until they can be cemented has been suggested by Cloud (1952b, p. 28) and others.

Observations on various Pacific atolls, have led to a divergence of conclusions concerning the areas in which beachrock is currently developing. On Bikini Atoll, according to Ladd and others (1950, p. 416), "beachrock may be formed between the reef flat and the beach." These authors refer to the fresh look of the rock and the original color of organic inclusions as evidence that lithification is going on today, but also point out that exposed parts of the beachrock are being eroded. On Onotoa Atoll, a "bonded limesand," described by Cloud (1952b, p. 28) is considered incipient beachrock, forming on lagoon beaches, in tide pools, and in spray pools. Cloud states that it was not found on this atoll anywhere on the seaward beach. At Raroia Atoll, beachrock is recorded as rare along lagoon shores (Newell, 1954, p. 32), but is said to be forming in "moats" in the island interiors, behind lagoon-shore ridges, and especially back of seaward ramparts. This is probably the Cay sandstone of British and Australian geologists.

Most of the beachrock exposed at Kapingamarangi Atoll seems relatively old, as suggested by (1) the presence of beds preserved as relict deposits standing above present high-tide level on several islands, (2) the bevelled remnants of typical beachrock extending seaward a few hundred feet across the reef flat from the present island shores, and (3) evidence of replacement of calcium carbonate by apatite in strata both in the interiors and on the shores of several islands.

Although the seaward shores of most Kapingamarangi islands are undergoing erosion, there is reason to believe that some lime precipitation is going on contemporaneously. On the reef flat near Parakahi Island, a rectangle of boulders placed by man at an unknown date has been firmly cemented in place. On the east shore of Tirakaume Island, a 3-foot block of stratified limestone from an ancient outcrop of beachrock is now standing on end, incorporated in the present middle beachrock layer. How recently this development took place is not known, but it clearly shows a second stage in beachrock development. Recent, local precipitation of calcium carbonate on the seaward shores of islands is also indicated by records from other atolls. A fragment of green glass from a Japanese fishnet float, embedded in beachrock deposits at Bikini, is described by Ladd *et al.* (1950, p. 416), and the report of a firmly bonded gravelly sand containing brass cartridge shells on the seaward shore at Tarawa is recorded by Cloud (1952b, p. 29).

On Kapingamarangi Atoll no beachrock was found on the lagoon shores of the islands. Many test trenches were dug across various island beaches, and most of the beaches were examined in mapping the islands; all were of normal unconsolidated sand and gravel deposits. No clear evidence of beachrock development was found in the island interiors; "moats" periodically flooded by sea water as described by Newell (1954) for Raroia do not occur at Kapingamarangi. Thus, if beachrock is forming in appreciable amounts on the Kapingamarangi islands, it must be on the seaward sides. Most of the rocks on these sides, however, appear to be wearing away rapidly, so it is doubtful that beachrock development is extensive even there.

The theory that beachrock may develop by the work of ground water that dissolves calcium carbonate from lime sand and precipitates it as it seeps through the beach at low tide was proposed many years ago (Field, 1920, p. 215). Considerable evidence opposed to this theory has since been presented by Daly (1924, p. 138) and others. On the islands at Kapingamarangi, it clearly cannot apply because (1) intertidal sediments on the lagoonward margins of islands are not lithified, (2) bedrock on the seaward side rises above high-tide level and extends inland a considerable distance, and (3) no correlation between the water levels and island bedrock can be detected in the series of wells across Taringa and Werua islands (Figs. 6, 7).

Petrology

Character of Sedimentary Materials

Most of the sedimentary material that forms Kapingamarangi Atoll is calcium carbonate. Part of it is unconsolidated clastic particles. The remainder is lithified material developed by cementation of these clastic sediments and by the reef-building processes of corals, algae, and other organisms. Principal varieties of sedimentary rock have been classified into easily recognizable types, based primarily on texture and secondarily on the major contributing oragnisms or rock ingredients.

Sediments

Unconsolidated materials are separated into three groups according to particle size, follow-

ing the Wentworth classification of detrital sediments: (1) lime gravel (greater than 2 mm in diameter), (2) lime sand (between $\frac{1}{16}$ and 2 mm), and (3) lime mud (less than $\frac{1}{16}$ mm). All three groups form significant parts of the atoll, and each accumulates in characteristic situations. Both lime gravel and lime sand are concentrated on the reef flats, locally forming deposits from which the islands are built. They also cover much of the lagoon floor. Lime muds, on the other hand, are confined largely to the deepest parts of the lagoon.

Two principal varieties of lime gravel are recognized: one is boulder gravel, which contains angular blocks of reef rock, rounded coral heads, or masses of coralline algae which are of boulder (>10-inch) size. The other is formed almost exclusively of coral rubble, derived largely from broken fragments of *Acropora* or elk-horn coral ranging from half an inch to $2\frac{1}{2}$ inches in length. The boulder gravel indicates the action of violent storms and accompanying large waves, whereas the coral rubble is transported also by normal waves and currents and is being deposited almost continuously.

Lime sands of Kapingamarangi Atoll vary according to the combinations of organisms from which they have been derived. Those of the beaches and shallow off-shore waters are composed of the small orange foraminifer *Amphistegina madagascariensis*, the white wheel-shaped foraminifer *Marginopora vertebralis*, or both. Some beaches contain a high percentage of white mollusk shell fragments; elsewhere some beach sands consist of tiny, unbroken pelecypod shells forming coquinas. Shallow-water lime sands, especially on the tops of patch reefs, include large amounts of tiny coral fragments. In waters more than 80 feet deep, sands are formed almost exclusively of fragments of *Halimeda* (calcareous green algae) or of the hemispherical pale-olive foraminifer *Amphistegina lessonii*.

Pumice is abundant on the back-shore beaches of most islands. Much of it is of granule or small-pebble size, but a few fragments are as much as 6 inches in diameter. Most of the pumice is light gray; some is black. Many of the large specimens are well rounded. This material is so concentrated on some back shores that it forms essentially pure pumice layers.

Lime muds include (1) some small deposits of silt ($\frac{1}{16}$–$\frac{1}{256}$ mm) derived from shells or other organic structures, and (2) extensive deposits of very fine, pale-olive oozes which are sticky when wet. The silts develop at moderate depths in lagoon channels or other places where currents are strong enough to transport them. The calcareous oozes form only in the deepest parts of the lagoon bottom. They are composed of clay-sized calcium carbonate particles and some (about 10 per cent) very small Foraminifera of species not found in the shallower waters. This calcareous ooze has high plasticity and contains a slimy residue of organic matter conspicuous for its fetid odor when wet.

The mineral composition of Kapingamarangi sediments, as determined by A. J. Gude III with X-ray diffractometer patterns, varies according to the type of organism that dominates any particular sample (Table 3). The two common species of shallow-water Foraminifera and the common foraminifer below depths of 100 feet, *Amphistegina lessonii*, are composed of nearly pure calcite. In contrast, corals including *Acropora* and other common genera are predominantly aragonite except for a little calcite in their "dead" interior portions. Coralline algae of the genus *Porolithon*, which grow in abundance on the algal ridge of the outer reef, apparently are formed of calcite with a space lattice different from that of normal calcite. This feature is attributed by Gude to high magnesium content. Green algae (*Halimeda*) which contribute to lagoon sediment below 80 feet, contain about 98 per cent aragonite and small amounts of calcite. The bottom calcareous oozes are about three-fourths aragonite and one-fourth calcite.

Sedimentary Rocks

Rocks of calcium carbonate form the outer reef, parts of the islands on the outer reef, and patch reefs, within the lagoon. Four mappable varieties are recognized: (1) coral and coralline algal limestone, (2) aphanitic to stratified clastic limestone, (3) coral rubble limestone, and (4) boulder conglomeratic limestone. In some places recrystallization and other secondary modifications make it impossible to distinguish readily between (1) and (2); in many places (3) and (4) grade from one into the other.

Limestone from corals and coralline algae forms the framework of the outer reef and of the patch reefs and is developing wherever contributing organisms are growing, especially along the outer margins of the reefs. The rock developed from these organisms forms the pavement on the present bevelled reef surface. It is difficult to examine in section, however, because of its extreme resistance to breakage and because of the scarcity of exposed natural cuts into it. Samples from immediately below the pave-

ment surface commonly show relict structures of organisms, as might be expected, but many appear aphanitic as a result of secondary processes acting on the calcium carbonate. Although hand specimens commonly appear to be low in porosity, the rock mass is cavernous and contains many cracks, some of which are filled with clastic debris.

sizes and shapes similar to those in modern boulder ramparts. The coral rubble limestone is formed entirely of small rubble in a lime matrix. These clastic limestones are distinguished in mapping, as are their nonlithified equivalents, because of the different origins that they imply.

The varied mineralogy of different limestones on the atoll doubtless is in part due to secondary

TABLE 3.—MINERAL COMPOSITION OF KAPINGAMARANGI SEDIMENTS AS DETERMINED BY X-RAY DIFFRACTION PATTERNS

Locality	Horizon (feet)	Description	Aragonite	Calcite A	Calcite B*
Lagoon, W. of Matiro	228	Calcareous ooze	80	.....	20
Lagoon, W. of Romia	150	Calcareous ooze	60	.....	40
Lagoon, W. of Sokoro	216	Calcareous ooze	70	.....	30
Lagoon, W. of Tetau	224	Calcareous ooze	80	.....	20
Lagoon, Tokahui	186	Sand (*A. lessonii*)	.....	100	.....
Lagoon, Tokolala	90	Sand (*Halimeda*)	98	.....	2
Lagoon, Matamatong	5	Coral branch	99	.....	1
Lagoon, Matamatong	5	Core of coral	95	5	.....
Reef flat, Touhou	.....	Algal crust (*Porolithon*)	.....	.....	100
Reef flat, Touhou	.....	Algal crust (*Jania*)	.....	.....	100
Beach, Pungupungu	.....	Sand (shell fragments)	95	5	.....
Beach, south reef	.....	Sand (*A. madagascariensis*)	.....	100	.....
Beach, south reef	.....	Sand (*Marginopora*)	.....	.....	100
Beach, Matukerekere	.....	Clastic coral, weathered	10	.....	90

* Calcite A is interpreted as normal calcite; calcite B as magnesian calcite.

Aphanitic to stratified clastic limestone forms an appreciable part of the bedrock on all islands and occurs in many places on the reef flats as pedestals and raised ridges considered to be relicts of former islands. Where the rock is aphanitic, little can be determined concerning its origin. Where planes of stratification remain or are etched out on weathered surfaces and characteristics of grain are preserved, however, the history of the rock can readily be determined. Dips of cross-strata and other characteristics show close similarity to features of the unconsolidated deposits of island beaches.

Boulder conglomeratic limestone and coral rubble limestone are major constituents of most islands on Kapingamarangi Atoll and form conspicuous ledges and shelves along many of the seaward shores. The limestones are easy to recognize because the gravel within the lime matrix normally weathers into prominence and, in some places, is extremely conspicuous because of color contrasts. Boulder limestone includes angular blocks of reef limestone, rounded coral heads, and masses of coralline algae of many

processes of recrystallization and replacement. Many of the differences, however, are directly attributable to differences in the source materials. Foraminifera of which some rocks are composed are calcitic, corals in other rocks are aragonitic, and algal deposits in still others are high in magnesium (Table 3). Therefore, fundamental genetic differences may account for the different compositions of many of these youthful limestones.

On a few islands phosphorite rather than limestone locally forms stratified rock. Phosphorite, presumably developed from the guano of sea birds through replacement of calcium carbonate, occurs on parts of Pumatahati, Nunakita, and possibly a few other islands. It is an earthy, light-colored rock resembling the local limestone in texture and structure, but commonly lighter in weight, owing to high porosity. Mineral studies by Gude with X-ray diffraction patterns show that in some specimens the entire rock is composed of a variety of apatite.

Soils

General Statement

Soils of Kapingamarangi Atoll are necessarily young because the islands are of recent origin. Most of the soil profiles are classed as A-C profiles and consist of materials only slightly altered from the parent rock or sediment, covered by or mixed with varying amounts of dark humus. The soils show few features of well-developed horizons such as normally result from long periods of decomposition.

Kapingamarangi soils characteristically are well drained and alkaline. They are predominantly mechanical mixtures of organic material and gravel, sand, or fine calcium carbonate particles. They vary from dark brown to gray and creamy white. All soil profiles have dark layers at the top and light-colored bedded rock or sediment below, but some layers are separated by transition zones of intermediate color and composition, whereas others are marked by abrupt change.

Soil profiles were measured, and samples for analysis were collected from eight wells, dug in connection with ground-water studies, and from eight test pits. These profiles were distributed on seven islands as follows: Werua 3, Taringa 3, Parakahi 1, Pumatahati 3, Ringutoru 3, Tokongo 1, Rikumanu 1. Conclusions resulting from studies of the soil profiles and of the analyses of samples constitute the basis for most of the following discussion.

Parent Materials of Soils

The soils on the islands of Kapingamarangi are formed almost entirely from only two ingredients: (1) parent rock or sediment composed of calcium (and some magnesium) carbonate, and (2) humus from vegetable matter. The carbonate material varies considerably in physical form. Much of it is limestone derived from the bed rock; the rest of it occurs as unconsolidated sediment including gravel, lime sand, and lime mud. Large clastic fragments include blocks broken from the reef, coral heads, and masses of coralline algae. The small gravel is almost entirely coral rubble. Lime sand consists of shell fragments and tests of Foraminifera, with local contributions of the alga *Halimeda* and other organisms. The lime mud apparently results from the decomposition of stratified rock or of limestone blocks. All these clastic materials mixed with humus are relatively undecomposed even though they are in an area of prevailing warm, humid climate. This indicates very youthful soil.

Variations in the soils of Kapingamarangi are due to differences in the amount of original contamination and to the downward filtration of vegetable carbon into the calcareous host materials. High permeability of much of the sediment allowing rain water to enter readily, the penetration of roots as found in most test pits, and the work of animals all contribute to downward mixing. In some places a "transition" zone (A_3 horizon) in which small percentages of carbonaceous matter are mixed with coral rubble or lime sand has developed 12–15 inches below the normal (A_1 horizon) zone of incorporated organic matter. In other places no "transition" zone is present.

Appreciable variations in the chemical character of the island soils (Table 4) were not detected. In general, the youthfulness of the parent limestone precludes the possibility of any appreciable concentrations of noncarbonate minerals through leaching or decomposition. On the other hand, local additions to the soil may consist of pumice, guano, shells of crustaceans and echinoids, or skeletons of fish; possibly overflows of sea water have affected the soil in some places. Back-shore beaches composed almost entirely of pumice (Table 5) are present on the lagoon sides of several islands, and some pumice has been found in test pits, but its influence on vegetation is not known. Guano has contributed to the development of phosphatic soil on some islands, expecially Pumatahati, where according to native reports many frigate birds formerly roosted. Salts from sea water and sea spray that locally make soils highly saline have not left any conspicuous salt crusts, probably because evaporation is low as compared to influxes of fresh water; the salts do not seem to have affected large areas.

Alteration Processes

Showers on the islands normally are short but violent, and permeable surfaces allow most of the water to enter readily with a flushing effect that probably accounts for the general lack of saline residues. Migrating waters combine with carbon dioxide given off by plants to form carbonic acid which is active in the dissolution of limestone. Much evidence of such solution is seen in the bedrock.

At the low levels in the centers of some islands, especially where pits for growing

TABLE 4.—ELEMENTS IN KAPINGAMARANGI SOILS

Semiquantitative spectrographic analyses by Paul Barnett, U. S. Geological Survey. Elements reported by percentage ranges.

Well	Depth (inches)	Si	Al	Fe	Ti	Mn	P	Ca	Mg	Na	B	Ba	Cr	Cu	Pb	Sr
Werua #5	4	.01 .02	.02 .05	.1 .2	Not found	.002 .005	2 5	>10	.1 .2	.2 .5	.001 .002	.01 .02	.0005 .001	.001 .002	.0002 .0005	.5 1.0
Werua #5	20	.002 .005	.002 .005	.005 .010	Not found	.0002 .0005	.5 1.0	>10	.5 1.0	.2 .5	.001 .002	.0005 .001	.0002 .0005	.0001 .0002	Not found	.5 1.0
Werua #5	31	.01 .02	.01 .02	.02 .05	Not found	.0002 .0005	Not found	>10	.5 1.0	.2 .5	.001 .002	.002 .005	.0002 .0005	.0002 .0005	.0002 .0005	.5 1.0
Taringa #2	5	<.01	.02 .05	.05	<.005	.002 .005	5 10	>10	.1 .2	.2 .5	.001 .002	.002 .005	.0002 .0005	.0005 .0010	0	.2 .5
Taringa #2	20	<.01	.002 .005	.002 .005	<.005	0	0	>10	.2 .5	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0005 .0010	0	.5 1.0
Taringa #2	39	<.01	.002 .005	.001 .002	<.005	0	0	>10	.2 .5	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0002 .0005	0	.5 1.0
Taringa #2	55	<.01	.002 .005	.005 .010	<.005	.0002 .0005	0	>10	.5 1.0	.2 .5	.001 .002	.0005 .0010	.0005 .0010	.0002 .0005	0	.5 1.0
Taringa #3	2	<.01	.002 .005	.002 .005	<.005	.0005 .0010	0	>10	.2 .5	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0005 .0010	0	.5 1.0
Taringa #3	8	<.01	.002 .005	.001 .002	<.005	0	0	>10	.5 1.0	.2 .5	.002 .005	.0005 .0010	0	.0002 .0005	0	.5 1.0
Taringa #3	18	<.01	.01 .02	.01 .02	<.005	.0005 .0010	2 5	>10	.2	.2 .5	.001 .002	.002 .005	.0005 .0010	.0005 .0010	0	.5 1.0
Taringa #3	34	<.01	.002 .005	.002 .005	<.005	0	0	>10	.5 1.0	.2 .5	.001 .002	.0005 .0010	.0001 .0002	.0005 .0010	0	.5 1.0

The following elements were also looked for but not found:

Sensitivity limit	Elements	Sensitivity limit	Elements
.00005	Ag	.01	Li, Nd, Sb, Sm, Tl, W
.0001	Be, Yb	.03	Te, Zn
.0005	Co, Ge, Ni, Pd	.05	As, Ce, Dy, Hf, Ta, Th, U
.001	Bi, Ga, In, Mo, Nb, Sn, V, Y, Zr		
.003	Au, Pt	.5	K
.005	Cd, Er, Gd, Ir, La, Os, Re, Rh, Ru	1.0	Hg

puraka[2] have been excavated by the natives, ground water reaches the soil level and appears in places at the surface of the ground. Where this occurs, normal oxidation of organic matter is retarded or stopped by the water, and black mucks develop. The fresh-water lens, moving up and down in response to tidal fluctuations, apparently has a considerable solvent effect on calcium carbonate in the soil wherever it comes within range, as shown by the calcium bicarbonate content of water samples from the wells.

Nitrogen is added to the soil by legumes and some types of algae. Calcium carbonate introduced through evaporation does not seem to be important, for no caliches such as occur in arid or semiarid regions were observed, and fresh water above the water table appears to be removing rather than contributing calcium carbonate.

Burrowing animals such as land crabs and earthworms speed up the formation of soil through the mixing of materials and by facilitating aeration of the ground. These animals are abundant in most islands. Roots which penetrate and break up soil materials are especially effective in the upper two feet of soil and sand, as seen in wells and test pits. Few roots were observed below depths of 4 feet, however.

[2] A plant with a tuberous, starchy root, related to the taro.

Relation of Soil to Position on Island

Because seaward and lagoonward parts of most islands on Kapingamarangi Atoll differ considerably in age, the stage of soil development on each side varies. On large and medium-sized islands the seaward sides are composed largely of limestone bedrock, believed to be relict from deposits of a former and higher stage of sea level; they are overlain in most places by rubble. In contrast, the lagoon sides of these islands are formed of relatively recent beach and bar deposits such as are now developing along the lagoon shores.

Excavations representative of the seaward and lagoonward sides and the centers of islands demonstrate the differences in their soil profiles. Wells and pits located approximately 100 feet from the lagoon beaches of Ringutoru, Taringa, and Werua islands show soil layers of 2½-, 2- and 5-inch thickness, respectively (Figs. 4, 6, 7). Soil layers measured near the centers of the same islands are 8, 11, and 15 inches thick, and on the seaward sides 8, 14, and 32 inches. Small islands like Rikumanu and Tokongo, composed largely of bedrock from an earlier stage of sea level, probably correspond in age to the seaward portions of the larger islands. Commensurate with this age, soil layers of 29 inches on Rikumanu, and 18 and 7 inches on Tokongo were noted in test pits (Fig. 5).

Buried profiles occur on the seaward sides of at least three islands and may be expected on others. On Ringutoru, Taringa, and Werua the soil profiles (Figs. 4, 6, 7) include a relatively thin upper layer of dark-brown soil, separated from a lower, much thicker soil by 9–24 inches of light-gray sediment, including sand, coral rubble, and small amounts of humus. This light-colored layer probably represents an interruption in the soil-development process, during which time waters deposited clastic sediments. It is postulated that this deposition was a result of sheet wash at a time of storm activity. Much sand and some rubble, but no coarser materials, are included. The appreciable thickness of the overlying layer of soil (4–9 inches), which is comparable to that of the entire soil layer on the other side of the island, and the fact that buried profiles have not been found on the lagoon sides of any islands, indicate that a period longer than that required for development of the present lagoon side is responsible for this interruption in soil formation. Thus, although the buried profile may be the result of a recent storm, it more likely dates back to the time of an earlier sea stand.

Extremely youthful soil occurs locally where two islands have, within historic times, become joined through sedimentation facilitated by causeway construction. The natives are fully aware of the possibilities of increasing the size

TABLE 5.—PUMICE ANALYSES

Semiquantitative spectrographic analyses by Paul Barnett, U. S. Geological Survey. Elements reported by percentage ranges.

Element*	Gray pumice Matukerekere	Black pumice Hare Island	Element*	Gray pumice Matukerekere	Black pumice Hare Island
Si	>10	>10	Cr	.0001–.0002	.0001–.0002
Al	>10	>10	Cu	.0005–.0010	.001–.002
Fe	2.2–4.6	1–2	Ga	.0005–.0010	.0005–.0010
Ti	.2–.5	.2–.5	La	.005–.010	.005–.010
Mn	.05–.10	.05–.10	Mo	.001–.002	.001–.002
Ca	1–2	1–2	Nb	.005–.010	.005–.010
Mg	.5–1.0	.2–.5	Nd	.005–.010	.005–.010
Na	1–2	1–2	Pb	.0002–.0005	.0002–.0005
K	1–2	1–2	Sc	.0005–.0010	.0005–.0010
B	.001–.002	.001–.002	Sr	.05–.10	.02–.05
Ba	.05–.10	.05–.10	V	.001–.002	.001–.002
Be	.0002–.0005	.0001–.0002	Y	.005–.010	.005–.010
Ce	.01–.02	.01–.02	Yb	.0005–.0010	.0005–.0010
Co	.0002–.0005	.0002–.0005	Zr	.02–.05	.02–.05

*The following elements were looked for but not found: Ag, As, Au, Bi, Cd, Dy, Er, Gd, Ge, Hf Hg, In, Ir, Li, Ni, Os, P, Pd, Pt, Re, Rh, Ru, Sb, Sm, Sn, Ta, Te, Th, Tl, U, W, Zn.

of their islands by this method. Several illustrations of island annexation in various stages of development, are known. Near the south end of Hare Island, a small islet has been incorporated into the main island (Fig. 2). Remnants of a stone causeway about 150 feet long are still visible in the middle of the area though sediments have accumulated to a considerable

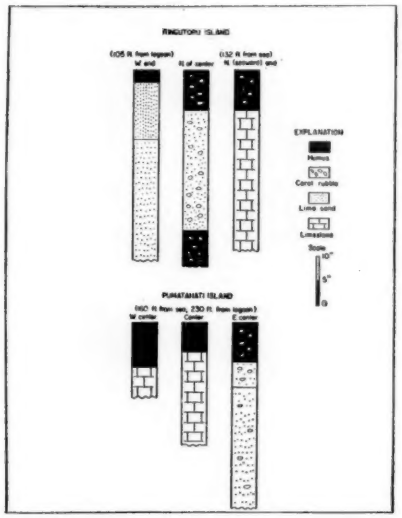

FIGURE 4.— TYPICAL SOIL PROFILES IN TEST PITS ON RINGUTORU AND PUMATAHATI ISLANDS

height on both sides of it. Seaward from the causeway an area about 300 feet long has filled in by natural processes, locally with sand and elsewhere with mixed sand and rubble. Soil has not yet developed. On the lagoon side sand and rubble have piled up on the shoreward part, leaving a depressed area inland toward the causeway; this low area is swampy and already has accumulated some black sticky mud.

According to soil nomenclature used on other atolls of the Pacific (Stone, 1951, p. 19–37), most of the soil at Kapingamarangi probably belongs to the Shioya soil series. This is especially true in the very young sediments on the lagoon sides of islands. In some places on the older, seaward parts of islands, development has gone beyond the Shioya stage, and more concentrated organic materials have resulted in a darker soil, perhaps of the Arno soil series. In these two soil types there is great textural variation both vertically and laterally. Such variations, as shown in test pits (Figs. 4–7), include organic materials that are relatively pure and others that are mixed with lime sand, coral rubble, or limestone blocks. Because nearly all the soils are developed on surfaces above the water table that allow rain water to pass through rapidly and that are conducive to relative dryness, mangrove swamps do not exist, and muck or peat is scarce. Only puraka pits and a few bomb craters where water accumu-

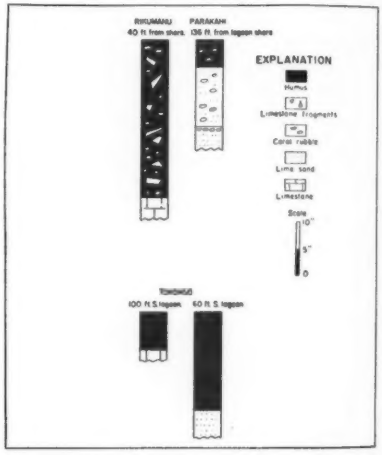

FIGURE 5.—TYPICAL SOIL PROFILES IN TEST PITS ON RIKUMANU, PARAKAHI, AND TOKONGO ISLANDS

lates permanently have an environment favorable to these soils.

Many illustrations of correlations between plant indicators and types of soil and sediment are apparent on Kapingamarangi. The constant association of *Scaevola* with sandy beaches and of *Guettarda* with coarse rubble ramparts or with small islets covered by rubble are examples. This subject has been studied in detail by William Niering (1956).

DEVELOPMENT OF PHOSPHORITE

Phosphatic soils and rock phosphate or phosphorite occur at numerous places on the islands. The soils appear to be similar to other lime sand-humus soils, but X-ray diffraction tests show that they contain apatite in addition to calcite and aragonite and that a few samples consist entirely of apatite. In texture and structure the phosphorite or rock phosphate resembles the limestone from which it developed but is lighter in weight owing to high porosity. It varies from

light to dark brown and in general has a powdery, earthy appearance.

The phosphorite is attributed to phosphorization of salts in guano, involving reactions with foraminiferal or coral limestone. According to Aso (1953, p. 19) components of this type of phosphate normally are secondary calcium phosphate, $CaHPO_4$; tertiary calcium phosphate, $Ca_3P_2O_8$; and calcium carbonate in varying ratios. Thus, the phosphate probably represents an intermediate stage between fresh guano and tertiary calcium phosphate, the conversion taking place under the influence of organic acid and carbonic acid gas. The ease with which calcium carbonate is dissolved by phosphatic solutions is significant in this process (Aso, 1953, p. 17).

The distribution of phosphatic soils and phosphorite at Kapingamarangi and their concentration (Table 6) appear to have a significant relationship to the history of island development. At Pumatahati, test pit 1 near the island center shows complete phosphorization of limestone in both soil and stratified rock to a depth of 2 feet or more (Table 6). Test pit 2, farther east on the same island, shows only a little apatite present, and it is near the surface. The fact that surface soil is affected in both places suggests recent development. High concentration in the central area is expectable, for this island is reported by the natives to have been the roosting place of large numbers of frigate birds for many years.

Concentrations of phosphatic soil are recognized on several islands other than Pumatahati. These include Taringa (Table 6) and Werua

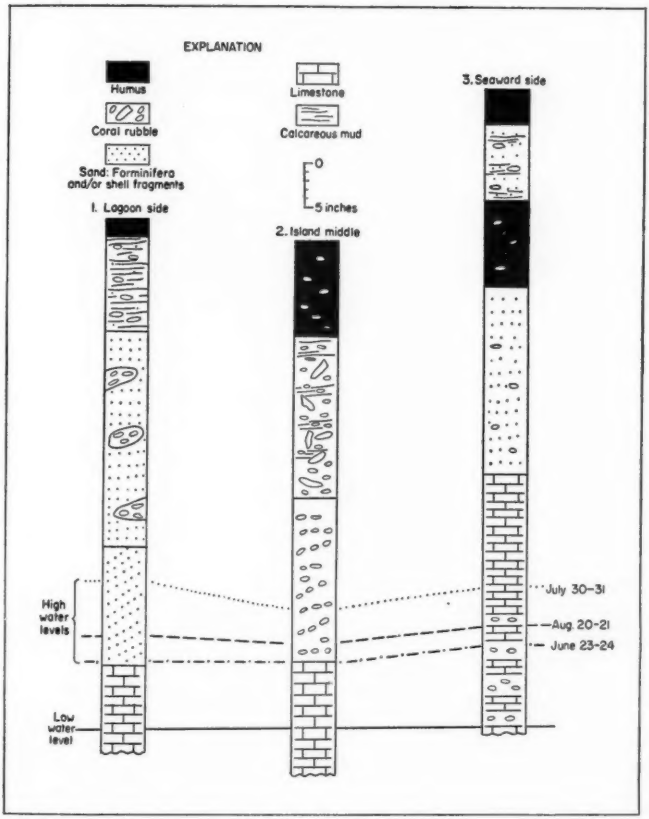

FIGURE 6.—LITHOLOGY AND WATER LEVELS IN WELLS ON TARINGA ISLAND

(Table 4) and probably others for which analyses have not been made. The localization of apatite near the soil surfaces on these islands suggests that its development may be relatively recent. Phosphorite comprising the stratified rock on certain other islands, however, apparently formed before the islands had migrated to their present positions. On Ringutoru and Rikumanu, for instance, high-level remnants of stratified rock on the island margins, considered to antedate the latest fall in sea level, are highly phosphorized. On Hare, Nunakita, and Rikumanu, stratified rock that is on the seaward shores, beyond the outer fringe of vegetation, and is periodically covered by high-tide waters, is also high in apatite (Table 6). These deposits are interpreted as relics from a time when they were in island interiors, such as the frigate birds inhabit today, and when birds in numbers frequented the areas.

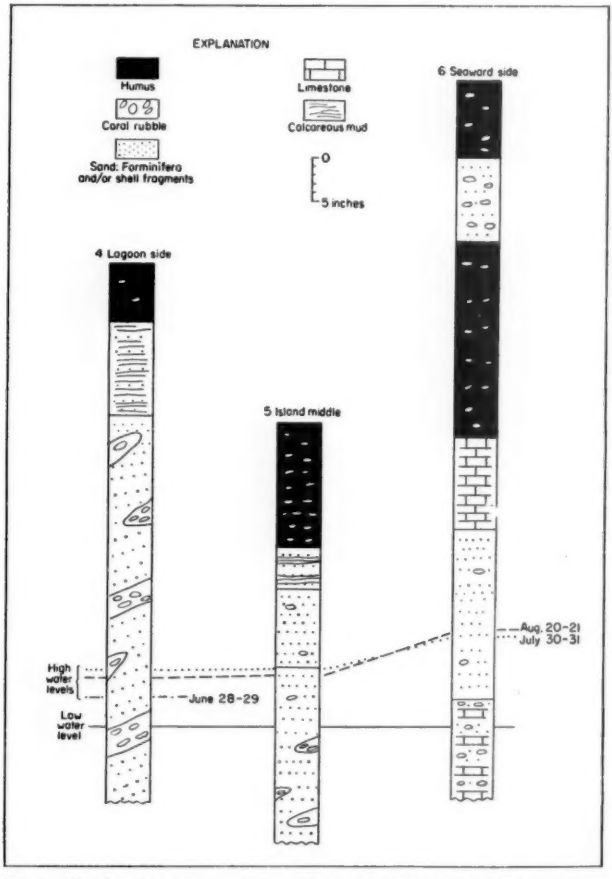

FIGURE 7.—LITHOLOGY AND WATER LEVELS IN WELLS ON WERUA ISLAND

GROUND WATER

General Features

Fresh or brackish ground water floats on the denser salt water within rocks of most small islands and assumes a lens shape. These facts have long been recognized by hydrologists, and the name "Ghyben-Herzberg lens" is used in referring to the body of fresh water (Stearns and Vaksvik, 1935, p. 237–239).

On Kapingamarangi Atoll most of the islands contain ground water of varying degrees of

freshness. On the larger islands this water is potable and of sufficient quantity for domestic use. The natives have dug wells penetrating it, but they usually prefer cistern water for drinking. This is fortunate, for the wells near the places of habitation are apt to be polluted. In the village on Touhou, water from the community well is used for washing purposes; much of it is carried in buckets to bath houses, but some is used in the immediate vicinity.

Because of droughts the supply of cistern water periodically becomes low and locally is exhausted. At such times the ground water of the islands is an important supplementary supply of potable water. Factors that control the location, quality, and amount of this water are similar to those described in connection with the ground water of other atolls (Cox, 1951; Arnow, 1954), but climate, lithology, and terrain are responsible for local variations and make an analysis of the local water problems desirable.

TABLE 6.—PERCENTAGES OF APATITE AS DETERMINED BY X-RAY DIFFRACTION ANALYSES
Data from James Gude, U. S. Geological Survey

Island	Stratigraphic Position	Depth (inches)	Apatite (per cent)	Comments
Ringutoru	High-level remnant	0	50	Relict bedrock
Rikumanu	High-level remnant	0	75	Relict bedrock
Rikumanu	Stratified shore deposits	0	20	Relict bedrock
Rikumanu	Stratified shore deposits	0	40	Relict bedrock
Nunakita	Stratified shore deposits	0	30	Relict bedrock
Hare	Stratified shore deposits	0	20	Relict bedrock
Pumatahati	Soil, top	3	100	Pit 1, near island center
Pumatahati	Upper bedrock	8	100	Pit 1, near island center
Pumatahati	Lower bedrock	20	100	Pit 1, near island center
Pumatahati	Top soil	4	2	Pit 2, eastern interior
Pumatahati	Transition soil	11	2	Pit 2, eastern interior
Pumatahati	Unconsolidated	22	0	Pit 2, eastern interior
Taringa	Top soil	5	50	Well 2, near island center
Taringa	Transition soil	25	0	Well 2, near island center
Taringa	Coral rubble	40	0	Well 2, near island center

Objectives of Investigation

Ground-water studies on Kapingamarangi Atoll, made periodically during June, July, and August of 1954, were conducted on Taringa, Werua, Parakahi, and Hukuniu. These islands were selected because of accessibility and because they were considered representative. Taringa is a moderately long but narrow (600 feet) island with stratified rock forming the seaward shore, and sand beaches forming the lagoon shore. Werua is considerably wider (1000 feet) and has more variation in topography resulting from larger size. Parakahi is small (400 feet by 300 feet) with a surface composed entirely of unconsolidated sediments. Hukuniu is very small (250 feet by 150 feet) and stratified rock forms all its shores and surface, except where a thin mantle of humus occurs in the interior.

The objectives of the ground-water investigation were to obtain data on (1) the depth to water in various parts of the islands, (2) the amount of change in water level as compared with tidal changes in adjoining sea and lagoon, (3) the amount of lag between the extremes of tide and the corresponding changes represented in well levels, (4) the effects of permeability in different types of rock and in unconsolidated sediment, (5) the variations in ground-water

lenses resulting from differences in size of islands, and (6) the quality of the water resulting from various situations.

Methods of Study

Eight wells—three on each of the large islands and one on each of the small islands—were dug to a depth below the lowest level of the water table for each area involved. Records were made of the types of sediment penetrated (Figs. 6, 7), and a staff gage was installed in each well for measuring water fluctuations. Three times during the summer hourly readings were made for 24-hour periods to obtain from this series of wells relative measurements of the times and extent of water fluctuations. Some water samples were analyzed in the field for salinity and pH. Others, representative of all the wells, were brought back to the U. S. Geological Survey in Denver, where analyses were made by John D. Hem.

The wells on both Taringa and Werua islands were dug in a row across the islands from west (lagoon shore) to east (seaward shore) and about midway along the length (north-south dimension) of each island (Fig. 2). The spacing (in feet) of the three wells in relation to the coasts on these islands was as follows:

	Lagoon to well 1	Well 1 to well 2	Well 2 to well 3	Well 3 to sea
Taringa	68	250	160	125
Werua	65	500	300	125

The single wells on the two small islands were dug near the centers. Locations (in feet) were as follows:

	From lagoon (W) side	From sea (E) side	From north side	From south side
Parakahi	136	288	145	156
Hukuniu	100	164	91	54

The wells on Taringa and Werua islands ranged in depth from 4 feet 2 inches to 7 feet 1 inch, depending on the depth to ground water at its lowest stage. The two deepest wells were those adjacent to the seaward coast. They were not located on boulder ramparts but on lower ground inland from the ramparts. These wells were the most difficult to dig, for stratified rock was encountered in each a little more than half way down.

Depth to Ground Water

As stated in the Ghyben-Herzberg principle, the highest part of the fresh-water lens within the rocks of most small islands is higher than sea level adjacent to the island. Because the ratio of fresh- to salt-water density that controls this lens is approximately 40/41, it follows that the elevation of fresh water above sea level is slight on islands the size of those on Kapingamarangi. Cox (1951, p. 22) and Arnow (1954, p. 3) show that an average height of about a foot is to be expected on the islands that they examined in different parts of the Marshall group.

Equipment was not adequate to measure the elevation of ground-water lenses with respect to sea level at Kapingamarangi. It seems safe to assume, however, that the elevation on any of those islands does not exceed 10–12 inches and in most places is much less. Thus, the water level on those islands may be regarded as roughly equal to sea level, and the depth to water in any well is approximately equal to the elevation above sea level of the surface at the well site. Because most of the lagoon margins of islands are slightly higher than the island centers and because the seaward margins are considerably higher than the lagoon margins, the depth to ground water normally is greatest near the seaward margins of the islands and and least near the centers. Figures 6 and 7, using low-water level as a datum plane (not allowing for the increase in elevation in the island center that results from the lens effect of the fresh water body), show the following depths (in inches) to the highest recorded water level:

	Lagoon side	Middle island	Seaward side
Taringa	43	43	58
Werua	48	29	66

These figures probably represent the approximate depths required to reach the upper limits of water on all the larger islands at Kapingamarangi, but to reach the level of permanent water (low-water level) an additional 8–12 inches is required. Further, if wells are to be used for domestic purposes, allowances must be made for normal drawdown, for lowering due to periods of little recharge, and for adequate storage, so additional depth is required. The depth should not be greater than necessary, however, or salt-water contamination of the wells may occur.

On the very small islands at Kapingamarangi, the water table is closer to the surface than on Taringa and Werua. This is due to lower topography. However, the amount of fresh water (if present at all on these small islands) nor-

mally is much less and the degree of salinity is higher than on islands with large recharge surfaces, as shown by the wells on Parakahi and Hukuniu islands.

Variations in Water Level

Water levels on atoll islands change gradually, as a result of increases or decreases in the amount of recharge, and they change hourly, owing to rising and falling tides that cause the salt water under the fresh-water lens to go up or down. Fluctuations due to gain or loss in recharge were not detected during the period spent on Kapingamarangi Atoll, though doubtless such changes were continuously affecting the water levels of all islands, especially the very small ones. On the other hand, significant data were obtained on the effects of tide on ground-water levels.

Figures 6 and 7 show the total rise and fall of water levels in the wells on Taringa and Werua on June 28, July 30, and August 20. The low-water level for each well, as measured with respect to the well bottom, was essentially the same for the three dates. The high-water levels, however, show marked differences, especially on Taringa, and these differences are directly related to tidal fluctuations as indicated by tide records. The amount of rise in the two wells located in island centers is slightly to moderately less than that of wells on the island margins. This difference undoubtedly results from incomplete readjustment of the fresh-water lens because of increased friction from distance of travel during the short intervals between tidal changes. It supports the principle (Cox, 1951, p. 14) that fluctuations in the water table of small islands are inversely proportional to distance from the coast.

Lag in Rise and Fall of Ground Water

The time between attainment of high or low stage by the tide in waters adjacent to an island and a corresponding level by the ground waters in the island varies according to the size of the island, the permeability of rock or sediment involved, and other lesser factors. This time is represented by a definite lag, which was 3–4 hours on Taringa Island and was 4–5 hours on Werua (Figs. 8, 9). On the small island of Hukuniu, however, there was virtually no lag (Fig. 10). This is attributed primarily to the high permeability, rather than to the small size, of the island.

Analysis of the charts of tide and well fluctuations (Figs. 8–10) shows that the lagoon tidal variation is consistently greater than the variation on the seaward side of the islands, but that, in the areas studied, the high and low tides arrive in both places at about the same time. Water levels in the wells on each island also show differences in amount of fluctuation, but on each island they reach their peaks at approximately the same time. These data suggest that differences in permeability as well as in distances from the shore and in tidal fluctuation at the shore are responsible for differences in the amount of rise and fall of the water table in any particular part of an island. Thus, in these small islands the fresh-water lens acts as a unit in so far as the time of rise and fall is concerned.

Relative Permeability of Sedimentary Materials

An asymmetry in the permeability of atoll islands has been indicated in the work of numerous geologists (Cox, 1951, p. 19). In most islands the lagoon shores are composed of beach sands, whereas the seaward shores are composed of stratified rocks, boulder ramparts, or both. The fine-grained sediment of the lagoon side is far less permeable than the coarse detrital fragments of the rampart or the cavernous limestone that constitutes much of the stratified rock. Fluctuations in the water table on atoll islands seem to be proportional to the permeability of the sediment or rock through which the water moves.

On Taringa and Werua the seaward coasts are formed of stratified rock up to and above high-tide level and of narrow boulder ramparts above the rock. The ramparts are not significant in so far as the movements of the fresh-water lenses are concerned, for, as illustrated in well profiles, all the ground-water movement on this side of the islands is within the stratified rocks. Furthermore, water from wells on the seaward side is definitely brackish, mostly not potable, which suggests that it enters through sizeable cavities or cracks with free circulation rather than by the slow percolation that constitutes intergranular movement in the sands. In contrast, ground water on the lagoon sides of these islands is fresh and drinkable almost to the beaches.

Parakahi and Hukuniu illustrate the effects of permeability on the ground water of very small islands. Well levels on Parakahi show approximately the same lag behind tide fluctuations as is found in wells of the larger islands.

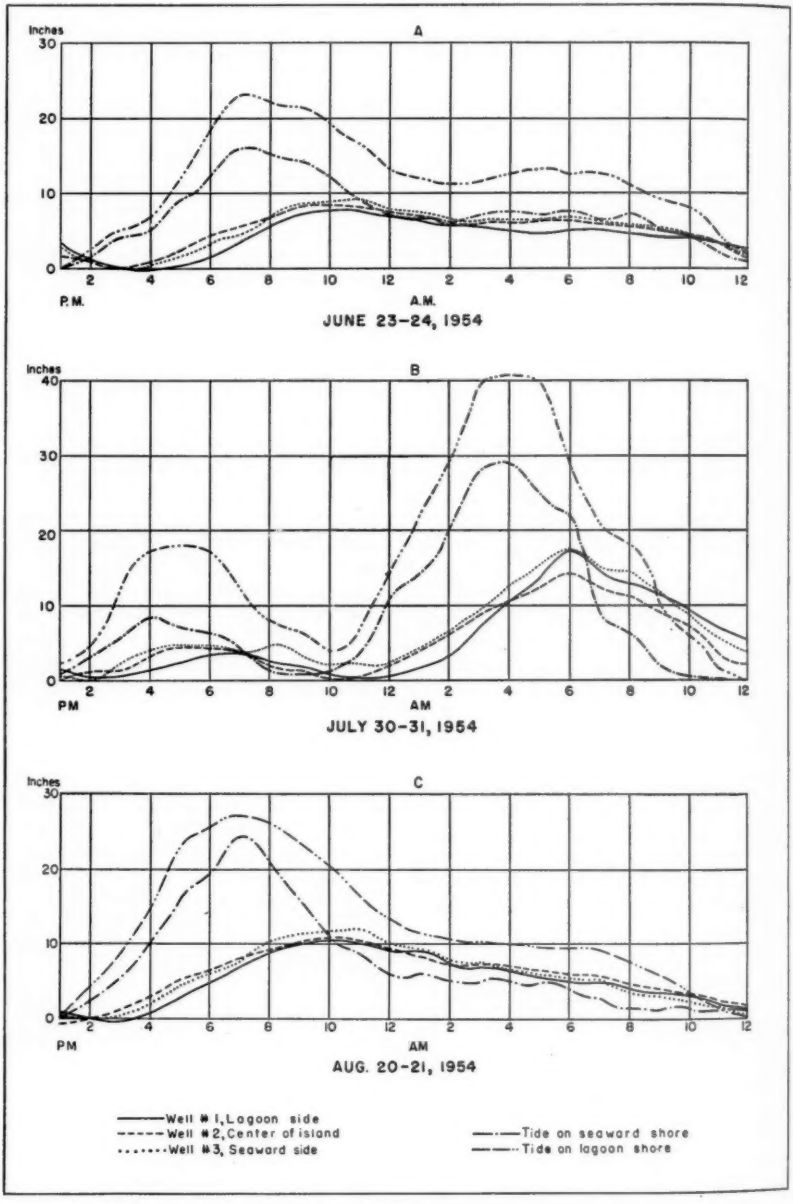

FIGURE 8.—TIDE AND WELL FLUCTUATIONS, TARINGA ISLAND

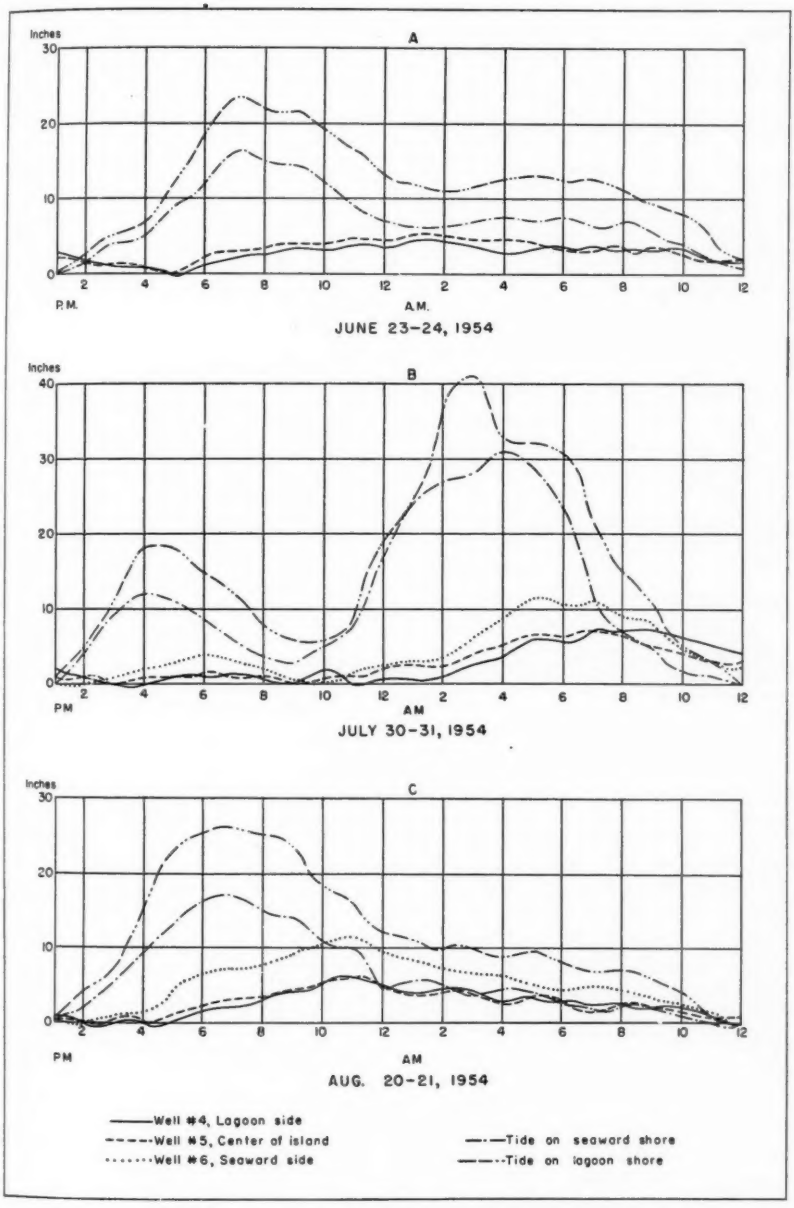

FIGURE 9.—TIDE AND WELL FLUCTUATIONS, WERUA ISLAND

The water, which is potable, must enter through sand deposits from any direction. In contrast, water level in the well on Hukuniu Island, which is formed almost entirely of stratified rock, islands, whereas on Hukuniu, where cavernous stratified rock is involved, the rise is considerably greater and approaches the corresponding total rise of the tide (Fig. 10).

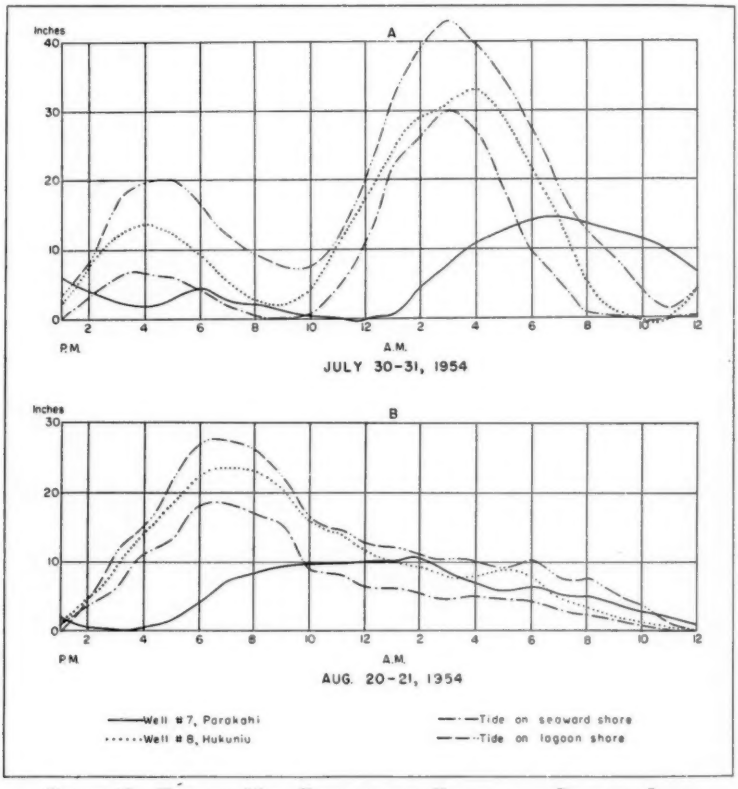

FIGURE 10.—TIDE AND WELL FLUCTUATIONS, HUKUNIU AND PARAKAHI ISLETS

reaches its high and low points at about the same times that high and low tides arrive. Furthermore, the salinity of the water in this well is close to that of sea water, again suggesting easy access through large channels.

Effects of Island Size on Lens

Observation wells in the centers of the two very small islands—Parakahi (400 feet by 300 feet) and Hukuniu (250 feet by 150 feet)—suggest that, on these islands, permeability of the rock or sediment, rather than size of the island, controls the amount of water-level rise and fall. On Parakahi the rise is comparable to that of wells dug in similar sediments on the larger

The real significance of island size in regard to the fresh-water problem is whether or not a lens can develop and be maintained. Because continued operation of a lens depends largely on the amount of recharge, a sizable surface area for catching precipitation and a sufficient amount of precipitation are necessary. Parakahi, a small island in a region of only moderate rainfall, is noteworthy for having a lens of fresh, potable water. Hukuniu, which is still smaller, has highly saline water, but this may be due as much to contamination from free circulation through large channels in limestone as to small size of the island. Thus, only a rough qualitative measure of the minimum size re-

quirement, furnished by the example of Parakahi, is available for Kapingamarangi Atoll.

Quality of the Ground Water

Water samples collected on August 20, 1954, from each of the eight test wells and analyzed by the U. S. Geological Survey are summarized in Table 7. Well waters from Taringa and Werua are progressively higher in chemical components, total hardness, and percentage of sodium from the lagoonward to the seaward side. This trend almost certainly is related to the amount of mixing with sea water and probably results from differences in permeability of island sediments and rocks. The cavernous rock beds on the seaward sides apparently allow greater mixing than do the sands on the lagoonward sides.

Table 7.—Analyses of Water Samples From Test Wells and Comparative Data for Normal Sea Water

(Analyses by U. S. Geological Survey)

	Taringa			Werua			Parakahi	Hukuniu	Normal sea water
	1	2	3	4	5	6	7	8	
Chemical components (ppm)									
Calcium (Ca)	89	174	255	132	194	368	258	517	400
Magnesium (Mg)	24	63	249	12	13	204	54	1,160	1,270
Sodium (Na)	38	560	2,010	22	23	1,580	400	9,390	10,560
Potassium (K)	2.4	18	75	3	2.4	55	12	359	380
Sulfate (SO_4)	16	4.1	459	1.2	4.1	288	30	2,290	2,650
Chloride (Cl)	55	1,100	3,810	20	18	2,980	875	17,500	18,980
Physical characteristics									
Hardness (ppm)	320	693	1,660	379	538	1,760	866	6,060	6,215
Percent sodium*	20	63	71	11	8	65	50	76	79

*Percentage of sodium among the principal cations (sodium, potassium, calcium, and magnesium), all expressed as chemical equivalents.

Comparison of water from the two small islands, Parakahi and Hukuniu, shows differences similar to those noted from one side to the other of the large islands, but contrasts are greater. These contrasts apparently also result from variations in permeability and in degree of mingling with sea water. Water from the Parakahi well illustrates relatively poor mixing; that in the Hukuniu well has nearly the composition of sea water.

The hardness of the well waters undoubtedly reflects contributions of calcium and magnesium from limestone and lime sand. The hardness increases across Taringa and Werua from lagoon to sea, reflecting an increase in the degree of mixing of ground water with sea water. Calcium is much higher than magnesium in the near-lagoon samples, reflecting solution of calcium carbonate and relatively little mixing with sea water, whereas calcium exceeds magnesium only moderately in the near-sea samples, reflecting mixing with sea water, which has proportionately more magnesium.

The hardness of water from wells on the lagoon sides and in the island centers ranges between 300 and 700 ppm. By comparison, most water classified as soft in the United States is below 50 or 60 ppm. The island waters would require "water softeners" for domestic use in America. They are similar in quality to waters from the northern Marshall Islands recorded by Arnow (1954, p. 7).

Water samples from test wells on Taringa and Werua were checked numerous times during the summer for pH and temperature. The pH readings ranged from about 7.0 to 7.5, and those from the relatively brackish waters of wells on the seaward side were consistently high, apparently reflecting a slight alkaline increase from sea-water mixing. Temperature for all well waters was 27.5°–28° C. (81.5°–83° F.) in the early morning but commonly rose 1°–2° C. during the day.

Water from wells on the lagoon margins of islands is generally more potable than that from other parts and is easier to reach by

digging. Probably all wells thus situated will furnish water of good quality which, if protected from pollution, can be used to advantage by the Kapingans. The U. S. Public Health Service recommends 250 ppm of sulfate (SO_4) and chloride (Cl) as upper limits for water used in normal domestic consumption, although water considerably higher in these components

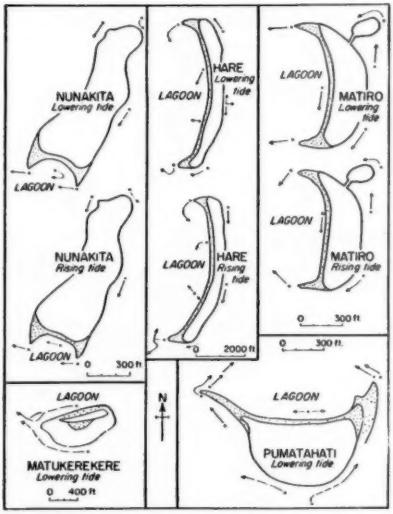

FIGURE 11.—NEAR-SHORE CURRENTS OF TWO SOUTHERN, TWO EASTERN, AND ONE NORTHERN ISLANDS OF KAPINGAMARANGI

of near-shore currents, records were tabulated on the direction and relative rates of movement with respect to nine islands (Figs. 11, 12). Three islands,—Nunakita, Torongahai, and Ringutoru,—are in the northern section of the atoll; four,—Werua, Matiro, Hare, and Taringa,—are on the eastern side, facing the dominant wind direction; two,—Pumatahati

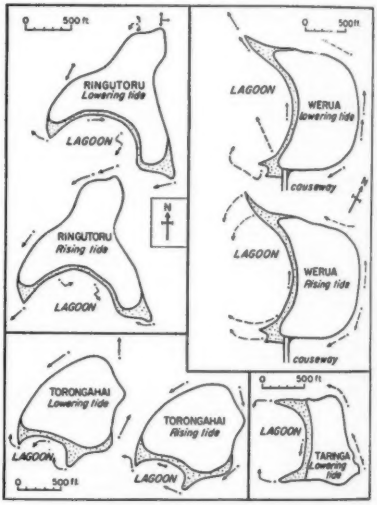

FIGURE 12.—NEAR-SHORE CURRENTS OF TWO EASTERN AND TWO NORTHERN ISLANDS OF KAPINGAMARANGI

may be used without apparent harm by people who have become adjusted to it. Water from the island centers is moderately good, but that on the seaward sides is too brackish for domestic use.

NEAR-SHORE CURRENTS

Currents moving along the shores of the Kapingamarangi islands are, in part, normal longshore currents generated by waves and, in part, the results of tides. They contribute to erosion and deposition and are significant in maintaining ventilation within the lagoon by introducing and ciculating new sea water with each rise in tide. The tide rises 6–13 inches higher within the lagoon than it does on the seaward sides of the islands (Figs. 8–10), probably because the passes between islands form constrictions that limit the movements of water.

To obtain specific data on the movements

and Matukerekere,—are on the southern arc. To observe currents, fluorescein dye, which produces an orange color readily observable even at a distance, was poured in the water. Movements recorded at times of both rising and falling tides were plotted for contrast.

Observations on near-shore currents (Figs. 11, 12) show that on the seaward sides of most islands tidal currents normally move in opposite directions from a central point. During rising tides, however, longshore currents may develop with sufficient strength to direct all movement in one direction. On the concave lagoon sides, near the sand beaches, which are protected by horns or bars at the island extremities, current movement is extremely small at most times and has no dominant direction.

The most significant current movements adjacent to islands are those passing between the islands. These are especially effective during rising tides. Such currents travel consistently toward the lagoon, moving clastic sediments

and building rubble and sand bars out into the lagoon from the ends of each island. Furthermore, between the bars of adjacent islands these currents produce submerged reef-deltas that protrude well out into the lagoon. The reef-deltas are prominent in airplane photographs and are conspicuous even from a boat; normally they are composed dominantly of coral rubble in their headward parts and of foraminiferal sand in deeper waters beyond.

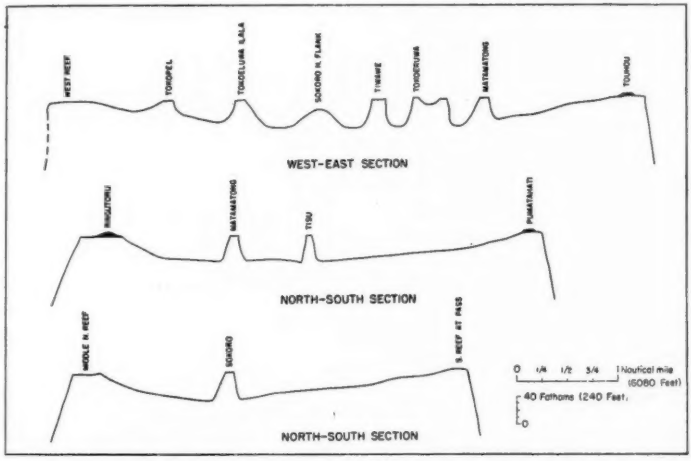

FIGURE 13.—SECTION ACROSS KAPINGAMARANGI LAGOON
(Vertical exaggeration approximately ×30)

Because bare reef flats with little sand occur seaward of the Kapingamarangi islands,[3] little sediment has accumulated on this side. Shores at and below sea level are largely of stratified rock, which shows the effects of planation as should be expected from known current trends. The few lime sands that wash into this area normally are moved along by currents and waves through the gaps between islands and thence into the lagoon. Even the considerable amounts of coral rubble from the reef edge seem to be transitory. Only the ramparts of boulders or rubble that stand above high-tide level and are formed by the waves of occasional large storms form significant deposits on seaward parts of the islands.

In the near-shore waters on the lagoon sides of islands, protected from the prevailing easterly winds by the islands and from tidal currents by the horns or bars at island extremities, the normal, extremely weak and variable currents seem incapable either of depositing or of removing beach sediments. Most of these beaches are of foraminiferal sand, and the species represented appear to live in the shallow waters near by, but their accumulation and that of coral rubble as found at Hare and some other islands probably result from the occasional reversals in wind direction, which bring waves from west to east across the lagoon. These wind reversals result in a piling up of water and sediment against lagoon shores of the islands.

Pumatahati (Fig. 2) is unique in that its lagoon beach is formed almost entirely of coral rubble rather than sand and in that it has a well-developed rubble rampart on the lagoon side. Both features are the results of the action of large waves caused by strong winds. Furthermore, the winds must have come from the east across the lagoon, because the source of rubble on the rampart and the greatest concentration of rubble on the beach are at the eastern end. Such features probably developed on this island and not on others because of its far westerly position on the southern reef.

SEDIMENTATION IN THE LAGOON

The Kapingamarangi lagoon covers about 15.5 square miles and has maximum dimensions of 5 by 6 nautical miles (Nugent, 1946, p. 755).

[3] This is in contrast to the conditions on Nukuoro and certain other atolls where Foraminifera (*Calcarina*) live in abundance on the reef flat outside the islands and form extensive sand deposits.

It is roughly circular with an almost straight southwestern side. Profiles of the lagoon bottom, in spite of the many irregularities caused by patch reefs that rise from it, are those of a asymmetrical distribution of the deepest areas, resulting in gentle slopes on the south and west sides of the lagoon, Nugent (1946, p. 756) postulated that Kapingamarangi "is

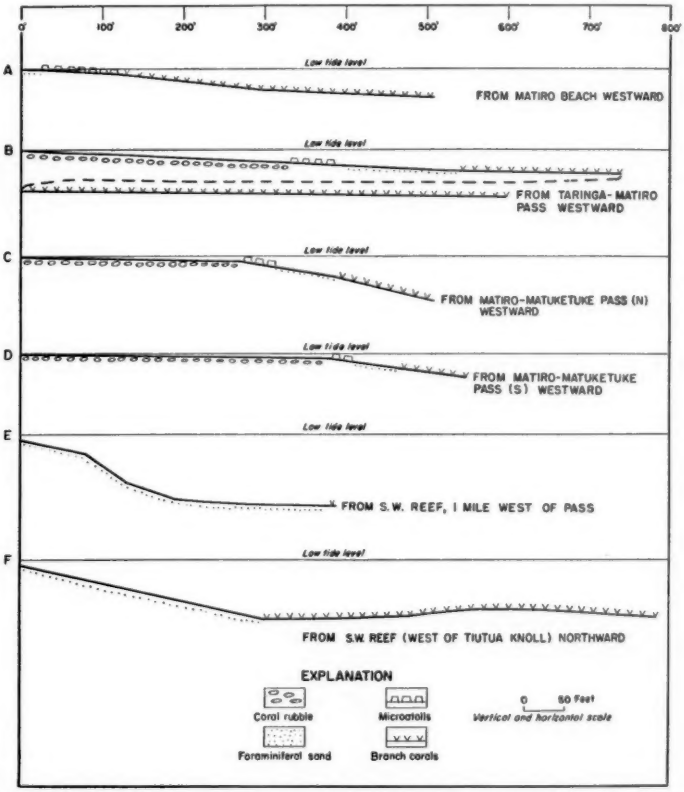

FIGURE 14.—OFF-SHORE PROFILES IN EAST AND SOUTH SECTIONS OF ATOLL AND DISTRIBUTION OF BOTTOM SEDIMENTS

shallow basin (Fig. 13). Even with the greatly exaggerated vertical scale used in the sections, the slope appears gentle, and sections of near-shore areas (Fig. 14) and of Manin knoll (Fig. 15), made with the same vertical and horizontal scales, demonstrate the gentle slopes in which sediments are accumulating.

The deepest parts of the lagoon, in the north-central and east-central areas (Fig. 1), are recorded as 43 fathoms on U. S. Navy Hydrographic Office Chart 6042. The greatest depth measured by the writer in more than 200 soundings was 40 fathoms (240 feet); this depth was reached in at least five places, suggesting a relatively flat bottom. Because of the slightly apparently tilted to the northeast." This feature of distribution can be explained in other ways, however, and the relative narrowness of the southwest arc of the atoll as compared to the northeastern arc argues against the postulate.

To obtain a detailed record of bottom sediments in the lagoon, samples were collected systematically along many lines forming a modified grid pattern. Both grab samples and bottom drags were employed; in relatively shallow waters samples were obtained by diving. Approximately 250 samples, representative of almost all parts of the lagoon, were collected. These samples are being studied in

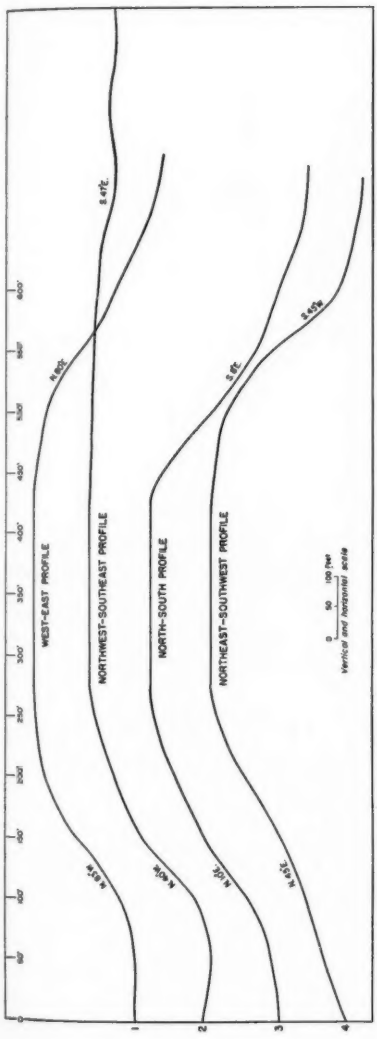

FIGURE 15.—PROFILES OF MANIN PATCH REEF

detail and will be reported upon in a subsequent publication.

A relationship between type of sediment and depth of water (Fig. 16) is apparent in the lagoon at Kapingamarangi. Of seven principal types of sediment recognized, six are restricted to relatively narrow limits in depth, forming a series of bands encircling the deepest parts of the lagoon. The seventh type of sediment is a white silt, apparently formed of comminuted shells, corals, and other debris; it is distributed along the paths of strong bottom currents at depths ranging from a few feet down to at least 200 feet. The sediments and their general ranges are as follows:

1. Sand dominantly of Foraminifera (*Amphistegina madagascariensis* d'Orbigny, *Marginopora vertebralis* Blainville, and *Elphidium craticulatum* (Fichtel and Moll))—<50 feet; mostly up to 25 feet
2. Sand dominantly of clastic shell fragments—10–50 feet; mostly 25–50 feet
3. Coarse debris, predominantly of dead branch corals, accumulated between and below thickets of living corals—30–105 feet
4. Accumulations of *Halimeda macroloba* fragments—90–160 feet (patchy)
5. Foraminiferal sand (*Amphistegina lessonii* d'Orbigny)[4]—120–210 feet
6. Calcareous mud (containing aragonite needles and about 10 per cent Foraminifera)—150–240 feet

Sedimentary belts within the lagoon apparently represent the normal habitats of the various organisms involved, because a large proportion of samples show little mixing that would indicate transportation of organisms into pockets of accumulation by currents. Orange foraminiferal sand of near-shore areas (belt 1) grades outward and downward into white clastic sand of belt 2. There is very little gradation between the *Halimeda macroloba* sand of belt 4 and the *Amphistegina lessonii* sand of belt 5. Corals, especially branching types that cover the bottom surface mainly between depths of 30 and 90 feet, form an effective barrier in most parts of the lagoon between the sediments above and below these depths. Fragments of broken coral, many of them large, cover most of the lagoon floor between the living corals.

The calcareous mud which covers most of the lagoon bottom at depths below 34 fathoms

[4] Chief minor faunal elements are *Heterostegina suborbicularis* d'Orbigny and *Operculina ammonoides* (Gronovius); others associated are *Spiroloculina communis* Cushman and Todd, *Cibicides lobatulus* (Walker and Jacob), and *Planorbulinella larvata* (Parker and Jones). Identified by M. Ruth Todd.

(204 feet), but which has been obtained from stations as shallow as 25 fathoms (150 feet), is pale olive green and very plastic and sticky when wet. Mineral analyses made with X-ray diffraction patterns by A. J. Gude III show that much of this mud is aragonite, but it contains a small proportion of calcite. The calcite probably is attributable to the Foraminifera included. These form only a small percentage of the mud but are represented by a rich fauna including many genera and species. In a single sample from a depth of 36 fathoms, Ruth Todd of the U. S. Geological Survey noted 39 species. She reports the following as rough estimates of the percentage of the total foraminiferal fauna:

	Percentage
Cibicides lobatulus (Walker and Jacob)	20
Spiroloculina communis Cushman and Todd	20
Virgulina complanata Egger	10
Textularia agglutinans d'Orbigny *T. foliacea* Heron-Allen and Earland	12
Amphistegina madagascariensis d'Orbigny A. sp. (small, flat worm)	10

She notes (in a written communication) that "the remaining 28 per cent is composed of about 32 additional species among which one species each of *Tretomphalus*, *Globigerina*, *Cymbaloporetta*, *Loxostomum*, and *Operculina* make up the bulk (perhaps as much as 15 or 20 per cent of the whole fauna). The *Globigerina* is a planktonic form and the *Tretomphalus* is an attached form with a planktonic stage. *Cymbaloporetta* and *Cibicides* may be attached, but are not necessarily always attached. All the others are benthonic forms, so far as known."

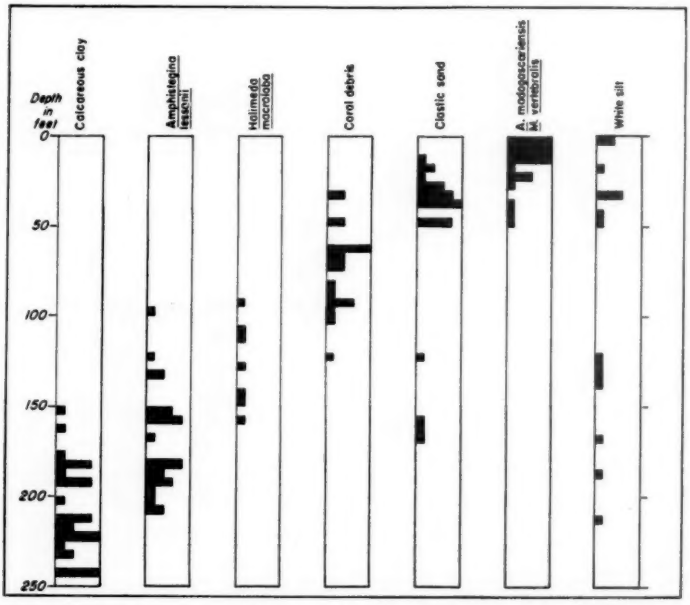

FIGURE 16.—RELATIVE PROPORTIONS OF PRINCIPAL TYPES OF SEDIMENT AT 5-FOOT DEPTH INTERVALS AS DETERMINED BY SAMPLING

The origin of the calcareous mud is not known, and detailed studies of it have not yet been completed. Evidence at hand suggests that the mud is not derived primarily from the residue of sediments occurring at higher levels. Although its composition is principally aragonite, it is surrounded by a belt of *Amphistegina lessonii* with a composition of normal calcite. If the aragonite were derived from either coral or shell debris of shallower depths, the difficulty of explaining how it bypassed the surrounding calcite belt is encountered. On the other hand, the presence of

some aragonite needles suggests that it may have formed as a chemical precipitate.

The over-all pattern formed by belts of sedimentation in the lagoon at Kapingamarangi is complicated by many patch reefs that rise of the atoll and within a mile of it, and in narrow zones bordering the western and northern arcs. The east-trending deposits of current-transported silts are prominent in airplane photographs of the southern part of the lagoon.

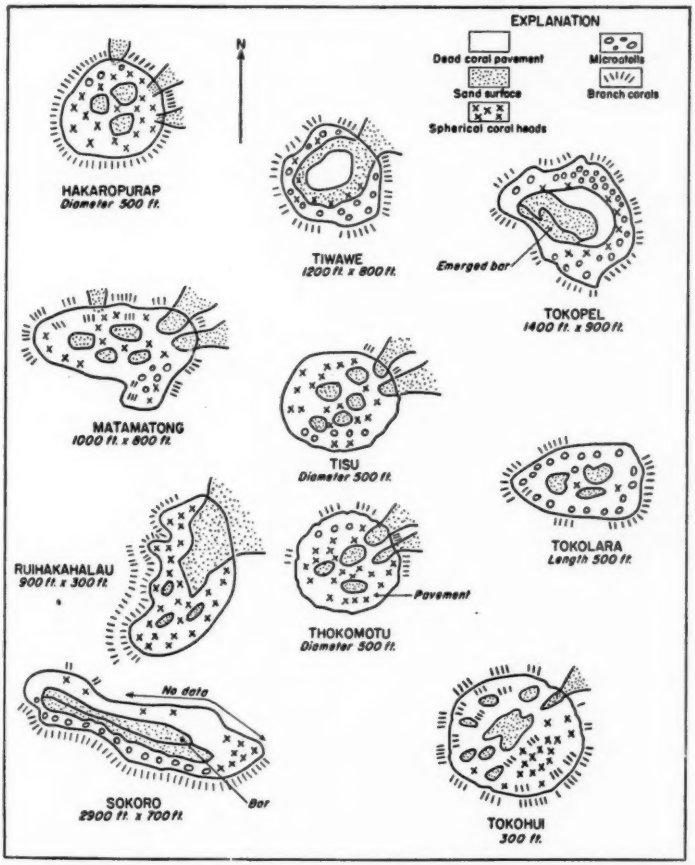

FIGURE 17.—FIELD SKETCHES OF PATCH REEFS SHOWING DISTRIBUTION OF SEDIMENTS AND CORALS

above the floor. Each of these has sediments on its top and sides in keeping with the general depth ranges, except that where slopes are especially steep the lower limits of various sedimentary types extend abnormally deep. Further complications in the pattern of sedimentary belts are caused by bottom currents in certain areas. The white silts characteristic of these current zones are especially well developed in and near the main pass on the south, in a broad area bordering the south side

The problem of why belts of sediment comparable to those in Kapingamarangi lagoon are not recognized in other atolls merits consideration. Differences in depth apparently account for the belts; most other lagoons that have been sampled are shallower than that at Kapingamarangi. Available descriptions indicate that belts corresponding to those of the relatively shallow waters do occur—*i.e.*, the belts of near-shore foraminiferal sand, of clastic sand, and of coral debris. At Raroia, in

the deepest parts (20–25 fathoms), Newell (1954, p. 25) reports a lack of bottom mud but records some accumulations of *Halimeda*. This distribution parallels that for corresponding depths at Kapingamarangi.

Geology of the Patch Reefs

The evenness of the bowl-shaped basin that contains the lagoon at Kapingamarangi is disrupted in many places by patch reefs that rise as mounds from its sides and floor. Many of these reefs are subcircular, but others are linear, and still others are very irregular. They range in size from low knolls or pinnacles a few dozen feet across and 10–20 feet high to wide platforms 100 feet high or more. Among the largest is Sokoro, whose top is 2900 feet long and 700 feet wide, and Tokopel, which has an upper surface approximately 1400 feet by 900 feet (Fig. 17).

The total number of patch reefs is not known, but 20 of those listed are more than 500 feet long. Available maps show approximately 75 of all sizes, yet even this number is probably conservative for many very small ones and others that do not reach the surface are not included. Counting of patch reefs is further confused because some reefs that appear separate at the surface are connected at shallow depths. Of the approximately 75 indicated on maps, 35 are in waters deeper than 60 feet, including some of the very large ones that rise from the deepest parts of the lagoon. Most of the other 40 patch reefs shown on the maps are small and occur in shoal waters bordering the inner margin of the atoll, especially along its northern and western sides.

Nearly all the patch reefs at Kapingamarangi have flat tops at or slightly above low-tide level, giving each mound the appearance of a mesa rising up through the lagoon. Only on a few of the submerged reefs do top surfaces appear to be somewhat rounded and irregular. Flat tops are characteristically developed and maintained in most patch reefs because the upward growth of organisms is controlled by tide levels and the surface is continually being bevelled by wave action. The sides are steep, in general, and commonly slope off at angles of 30°–40°. At some places they seem to be nearly vertical, but measurements show that most visual estimates are too high.

Table 8.—Depth (in Feet) of Lagoon Floor Surrounding Manin Patch Reef

Distance (in ft) outward from reef margin	Direction from reference point								
	N40°W	N10°E	N45°E	N80°E	S59°E	S47°E	S8°E	S45°W	N83°W
0	2	2	2	2	2	6*	2	2	2
75	24	24	30	18	18	12	54	12	12
125	48	48	60	54	24	24	90	42	42
175	90	84		80	30	20	108	102	78
225	102	102	96	102	30	24	126	120	90
275	96	108	114	114	30	24	132	126	90

* Along submarine ridge, 128 feet outward from 2-foot margin.

The general shape of Manin knoll in the northeastern part of the lagoon was determined from soundings (Table 8). This patch reef probably is typical of most at Kapingamarangi. Profiles (Fig. 15) show that its southwest side, in its steepest part, slopes down at about 50° within a vertical distance of 40–50 feet, and that the northwest side has a slope of about 40°. These are extremes, and other sides of the reef have more gentle slopes, including the southeastern sector, which extends as a slightly submerged promontory or ridge far out into the lagoon.

The distribution and orientation of patch reefs in the lagoon seem to reflect the trends of currents and waves. Thus a cluster of patch reefs, some of them large, near the ship's pass on the south side of the atoll probably is directly related to the strong currents that maintain good circulation in that area. The many small patch reefs immediately inside the northwestern and western arcs of the atoll apparently developed in response to waves of maximum fetch before the dominant winds. A general northwestward lineation of many reefs in the lagoon center probably also reflects this dominant wave direction. The subcircular outlines of most reefs are believed to be due to the relative quietness of lagoon waters.

allowing nearly equal growth in all directions, as suggested by Cloud (1952a, p. 2140).

All the patch reefs in deep water, and many of those in shallow, rise from parts of the amarangi patch reefs identified by J. W. Wells are listed in Table 9. The list indicates the principal forms, though others contribute to the reefs also. A comparison of these lists with

TABLE 9.—SOME CHARACTERISTIC CORAL ASSEMBLAGES ON KAPINGAMARANGI ATOLL Identified by J. W. Wells.

	Seaward margin outer reef at Touhou	Lagoon at Matiro Island 50–1000 feet out	Patch reef Tokohui	Patch reef Matamatong	Patch reef Thokotaman
Psammocora nierstraszi v. d. Horst			×		
Seriatopora hystrix Dana		×			×
Pocillopora damicornis (Linnaeus)	×	×		×	
danae Verril				×	×
eydouxi M. E. & H.	×				
Acropora corymbosa (Lamarck)	×				
digitifera (Dana)	×				
formosa (Dana)		×			×
striata Verrill					×
variabilis (Klunzinger)	×				
Astreopora myriophthalma (Lamarck)					×
Montipora composita Crossland				×	
sp. cf. *M. marshallensis* Wells					×
prolifera Brueggemann		×	×		
verrilli Vaughan	×				
verrucosa (Lamarck)			×		×
Pavona clavus (Dana)	×				
Herpolitha limax (Esper)					×
Goniopora sp. cf. *G. traceyi* Wells			×		
Porites andrewsi Vaughan		×	×	×	
fragosa Dana		×	×	×	×
lutea M. E. & H.	×			×	
Favia pallida (Dana)			×		×
stelligera (Dana)			×	×	
Favites abdita (E. & S.)		×		×	
Plesiastrea versipora (Lamarck)	×				
Platygyra rustica (Dana)				×	×
sinensis (M. E. & H.)		×			
Merulina ampliata (E. & S.)			×	×	
Cyphastrea microphthalma (Lamarck)		×	×	×	×
Heliopora coerulea (Pallas)			×	×	×
Millepora platyphylla H. & E.			×	×	×
tenera Boschma		×			×

lagoon bottom that are covered with extensive deposits of foraminiferal sand and calcareous mud. The patch reefs themselves, however, are mantled with growing corals. Dense thickets or forests of the yellow, branching *Porites andrewsi* cover most of the sides, and both micro-atolls and smaller coral heads, representing numerous species, cover extensive areas on the flat tops, especially along the margins. Typical coral assemblages from three Kapingthose of Wells (1954, p. 390–393) for the Marshall Islands shows that all the genera and all but two of the species of Kapingamarangi occur also in the Marshall Islands.

The surfaces of patch reefs, where not covered with living corals, are either occupied by accumulations of clastic and foraminiferal sands or are barren areas of dead coral. The proportion of each varies from reef to reef. The amount of dead coral areas seem to depend

on the elevation of the reef top with respect to low-tide level. For example, the top surfaces of Tokohui and Timan are 2 to 3 feet lower than those of most associated patch reefs (Fig. 17) and have no extensive areas of barren, dead coral. Their surfaces are largely covered with well-formed, growing corals. Few of the massive types of coral have dead centers or form micro-atolls, and many of the yellow, branching *Porites*, which on other knolls grow only on the margins and sides, are well developed even near the centers of these reefs. In contrast, on Sokoro and Tiwawe knolls, both of which stand well above low-tide levels, extensive areas of dead, bevelled coral occur in the centers, and micro-atolls are common along the tops (Fig. 17).

TABLE 10.—THICKNESS (IN INCHES) OF SAND ACCUMULATIONS ON PATCH REEFS

Patch Reef	Northeast margin	Center	Southwest Area
Tisu	6	5	5
Matamatong	11	7	....
Sokoro	....	18	16

Lime sand that accumulates on the upper sides and tops of most patch reefs is similar to that accumulating at corresponding depths off the lagoon beaches and lagoon reef margins of the atoll. This sand consists largely of orange tests of the foraminifer *Amphistegina madagascariensis* but contains varying amounts of small clastic particles derived chiefly from mollusk shells and corals. Some sand contains moderate amounts of locally derived *Halimeda opuntia* fragments. From field sketches of 10 representative patch reefs (Fig. 17), the characteristic distribution of sand is apparent. In general, sand is concentrated in the centers and on the northeastern margins, below which it commonly covers slopes down to depths of 20 feet or more. The thickness of sand accumulations on most patch reefs does not appear to be great (Table 10), and on some, where coral growth is especially luxuriant, sand is confined to small pockets. In contrast, Sokoro, Tokopel, and a few other knolls form sand bars of appreciable size that rise well above low-tide level.

Why sand that extends over the rims of the knolls is confined almost entirely to the northeastern slopes is not known. On other sides, in places where thickets of branching corals are absent, the slopes normally are covered with the debris of dead coral branches instead of sand.

As stated by Ladd *et al.* (1950, p. 421), "the age, origin and internal constitution of the knolls is not known, as no structure of this type has ever been drilled." They suggest that the patch reefs may have developed through sporadic coral growth that began during a part of the Pleistocene epoch, when sea level was much lower than now. Such a hypothesis agrees with the meager knowledge available concerning the shape of the lagoon basin, the extensive bottom sands and muds that are helping to fill it, and the patch reefs that rise to low-tide level within the lagoon. Furthermore, the bevelled surfaces of dead coral, back from the actively growing rims on most of the high knolls, strongly suggest that like the outer reef of the atoll, they were higher than at present not far back in history and have been truncated because of a recent drop in sea level. From what may be observed of their simple shape and structure, it seems probable that these patch reefs are similar in all essential respects to the bioherms that have been described from many ancient deposits, especially those of Silurian and Devonian age (Shrock, 1939).

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DIMENSIONAL ANALYSIS APPLIED TO FLUVIALLY ERODED LANDFORMS

BY ARTHUR N. STRAHLER

ABSTRACT

Dimensional analysis permits quantitative geomorphic studies to be placed on a sound geometrical and mechanical basis. Form elements of fluvially dissected landmasses are first analyzed according to dimension. Stream length, relief, length of overland flow, and basin perimeter have the dimension of length L. Drainage density, texture ratio, and curvature of profile have an inverse length dimension L^{-1}. Areal measures and volumes have the dimensions of length squared L^2 and length cubed L^3, respectively. Dimensionless parameters include stream-order number, stream azimuth, ground-slope angle, and channel gradient. Combinations of dimensional elements produce dimensionless numbers, such as stream-length ratio, basin circularity ratio, ruggedness " number, and hypsometric integral, which provide descriptive indices of the terrain, irrespective of scale.

Corrsin's dimension space is a useful graphic device for clarifying the dimensions of physical properties as unique vectors extending from an origin to appropriate points in space with respect to three orthogonal coordinates scaled in integer powers.

Application of dimensional analysis and the Pi Theorem to drainage density as a function of runoff intensity, an erosion proportionality factor, relief, fluid density and viscosity, and gravity yields four dimensionless groups: a ruggedness number, an erosion-intensity number (here named the Horton number), a Reynolds number, and a Froude number.

Complete geometrical similarity of landforms in two regions exists when all corresponding linear dimensions are in the same scale ratio, and all corresponding dimensionless numbers are the same. As an illustration, approximate similarity in planimetric form, but not in relief and slope, is established between small areas of mountainous terrain in the Verdugo Hills, California, and the Great Smoky Mountains, North Carolina. Examples from the Clinch Mountain area of western Virginia illustrate a case of extremely close similarity in landforms developed on different rock types and a case of striking dissimilarity where structural and lithologic controls are strong.

Accelerated land erosion, in which gullying results in badlands, is interpreted as a drainage-density transformation in response to sharp increases in the Horton number. Despite a many-fold increase in drainage density, the geometry number tends to be conserved by reduction of relief and increase of slope. Geometrical similarity is preserved in planimetric aspect but not in vertical aspect. The resultant system reaches a new steady state capable of exporting greatly increased load because of steepened valley-side and channel gradients.

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Introduction and Acknowledgments

Dimensional analysis as an operational tool of quantitative science has been widely used in engineering research, particularly in fluid mechanics, where inclusion of dimensional methods is standard practice in introductory textbooks (Rouse, 1938). Indeed, the theory of flow in viscous fluids and the similarity problem in hydrodynamic and aerodynamic scale models has forced the development of dimensional analysis and the formulation of well-known dimensionless numbers, of which the Reynolds and Froude numbers are perhaps most familiar. A comparatively recent development in physical science, the theory of dimensional analysis and dimensionless numbers appears to have been introduced in the 1880's and 1890's by Osborne Reynolds (1883) and Lord Rayleigh (1899). Application of the Pi Theorem was made by E. Buckingham (1914). Detailed treatments of the subject are given by Bridgman (1931), Rouse (1938), Langhaar (1951), and Duncan (1953).

Dimensional analysis was probably used by Gilbert (1914) in his flume experiments on transportation of debris, judging from a footnote on page 151, in which he uses the notations M, L, and T to mean mass, length, and time raised to various powers.

M. King Hubbert (1937) applied fundamental physical dimensions and the theory of similarity to problems of constructing working scale models in structural and dynamic geology. Krumbein (1942; 1944) used the Pi Theorem to reduce to 7 nondimensional groups 10 variables involved in flume behavior and settling velocity of particles as affected by grain shape; and to reduce to 6 nondimensional numbers 10 variables involved in relations among waves, currents, and sediment movement.

With an increasing trend in geomorphology and sedimentation to treat quantitatively the processes and landforms of erosion, transportation, and deposition, and to attempt analysis of the physical principles involved, it seems an appropriate time to introduce the concepts of dimensional analysis into geomorphology and thereby establish a firm base for quantitative work.

This paper is believed justified as a means of transferring an established analytical procedure from one scientific field in which it has proved of prime importance to another field where it has as yet seen little or no use, but where, by analogy, the future benefits seem great. Most of the ideas in this paper are borrowed, rather than original. Geomorphology would be greatly assisted in recovering its analytical activities by a number of such transfusions of ideas from a variety of scientific disciplines.

The author is greatly indebted to Professor William C. Krumbein of Northwestern University, who first called to his attention the possibilities of and need for dimensional analysis in geomorphology, and to Professor Richard Skalak of the School of Engineering of Columbia University, whose generous assistance made possible development of the illustrative example of Pi Theorem application. Dr. Laurence H. Nobles and Dr. Luna B. Leopold kindly read the manuscript and suggested various improvements.

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The Basic Concept of Dimensional Analysis in Empirical Science

From the broadest point of view, all science may be treated as consisting of two essential phases, empirical and rational.[1] Empirical science, often designated as "inductive science" in geological literature, is concerned with formulation of explanations and conclusions based upon observation of and experimentation with existing phenomena. When purely qualitative, as in much of geological science, the empirical method consists of receiving directly through the senses certain impressions about geological materials and structures, recording this information in words, and stating inferred cause-and-effect relationships or setting up classification systems. Thus, from sensory experience, a verbal description and explanation results.

In quantitative empirical science, information is also derived by observation and experimentation, but the attributes of the objects or phenomena of study must be described in terms of fundamental dimensional qualities, for each of which an arbitrary standard of measurement has been agreed upon. The fundamental dimensions present in classical Newtonian mechanics and thermodynamics (these being the principal branches of pure science involved in geomorphology and other phases of physical geology) are mass, length, time, and temperature. All geometrical properties which describe form, or morphology, can be reduced to length dimensions. All kinematic properties, involving velocities, accelerations, or periodicities reduce to the dimension of time, most of them in inverse relationship with length. All dynamic properties, involving masses in motion, can be reduced to some product relating mass to length or time. Thus, dimensional analysis forms an operational basis of quantitative empirical science.

When dimensional information has been obtained, the method of empirical science proceeds by statistical analysis toward the goal of establishing quantitatively the relationship between various dimensional quantities or groups of dimensional quantities. It is assumed that whatever the dimensional quantity measured, the data constitute a mere sample of an infinitely vast universe or population. Therefore, the population parameters must be estimated and the methods of mathematical statistical theory followed in establishing correlations and regressions between sets of observed dimensional data. Empirical laws of behavior of natural phenomena can thus be arrived at by means of systematic application of dimensional and statistical analysis.

As a specific example of the simplest sort, suppose that a student of sand dunes is investigating the relationship between the height of isolated barchan dunes and their distance from a source body of sand. In this study, both attributes measured have the basic dimension of length. A sample of 50 dunes selected at random yields 50 paired values of these two length dimensions. By means of regression analysis, it is established with reasonable likelihood that height of dune diminishes progressively with distance from sand source, and that the relationship is a simple linear one. A linear equation is derived and contains constants whose values are based upon the sample studied. This equation may be used for estimating one dimension when the other is known and it may be said that this quantitative relationship is typical of dunes in this area. But the equation is not necessarily based upon any theory of cause and effect derived from dynamic considerations; it is not necessarily connected with any understanding of the nature of the processes involved.

The rational phase of science, often associated with "deductive science" in geology, consists of the formulation of explanations and general laws through logical steps of reasoning from a series of initial postulates which seem to be valid in the light of prior observation and experience. A certain amount of intuition or insight is often involved in rational procedures, but the starting point of the process is usually traceable to empirically derived information. When rational treatment is quantitative, it takes the form of the development of mathematical equations of general form. Verification of the rational laws and establishment of the actual values for the constants, however, is a function of empirical science. A further discussion of rational procedures with an illustrative example in geomorphology is given elsewhere (Strahler, 1952a, p. 935–937). It will be shown here that dimensional analysis can be of great assistance in formulation of mathematical statements by rational methods.

[1] Rouse (1938, p. 1–2) discusses the long standing conflict between empiricism of civil engineers and rationalism of the mathematicians and physicists in dealing with problems of fluid flow. His discussion might be generalized to apply to any natural science.

TABLE 1.—DIMENSIONS OF FLUVIALLY ERODED LANDFORMS

A. Properties measured or counted solely from channel network and basin outline reduced to horizontal plane

Property	Recommended symbol	Where used or defined	How derived	Units	Dimensions
Stream order (basin order)	u	Horton, 1945, p. 281–282 Strahler, 1952b, p. 1120 Strahler, 1954, p. 344 Shykind, 1956, Ph.D. thesis, Univ. Chicago Melton, 1957, Appendix 1		Enumerative	0
Number of streams or basins of order u	N_u	Same as above		Enumerative	0
Bifurcation ratio	R_b	Horton, 1945, p. 286 Strahler, 1952b, p. 1137 Maxwell, 1955, p. 520 Schumm, 1956, p. 603	$R_b = N_u/N_{u+1}$	.....	0
Axil angle (entrance angle)	ξ	Horton, 1945, p. 349 Strahler, 1954, p. 345–347 Schumm, 1956, p. 617–620 Melton, 1957, Appendix 1		Degrees	0
Stream azimuth	α	Strahler, 1954, p. 346 Shykind, 1956, Ph.D. thesis, Univ. Chicago		Degrees	0
Stream length (channel length)	L	Horton, 1945, p. 283		Miles	L
Stream length, mean length of segments of order u	$\overline{L}_u$	Horton, 1945, p. 286 Strahler, 1952b, p. 1134 Strahler, 1954, p. 345 Strahler, 1957 Miller, 1953		Miles	L
Stream length, total length of order u	ΣL_u	Horton, 1945, p. 291 Strahler, 1957		Miles	L
Stream length ratio	R_L	Horton, 1945, p. 286–287	$\overline{L}_u/\overline{L}_{u-1}$	.....	0
Length of overland flow, or slope length	L_g	Horton, 1945, p. 284		Feet	L
Ratio of stream length ratio to bifurcation ratio	R_{Lb}	Horton, 1945, p. 292	R_L/R_b	.....	0
Basin perimeter	P	Smith, 1950, p. 657		Miles	L
Basin length	L_b	Schumm, 1956, p. 612		Miles	L

B. Properties requiring areal measurement (planimetry)

Area of basin of order u	A_u	Horton, 1945, p. 283		Miles^2	L^2
Basin area ratio	R_a	Schumm, 1956, p. 606	$R_a = A_u/A_{u-1}$	.....	0
Inter-basin area	A_i	Schumm, 1956, p. 608		Miles^2	L^2
Drainage density	D	Horton, 1945, p. 283	$D = \Sigma L/A$	Mi. per Mi.^{2}	L^{-1}
Constant of channel maintenance	C	Schumm, 1956, p. 607 Strahler, 1957	$C = A/\Sigma L = 1/D$	Mi.^{2} per Mi.	L

TABLE 1.—*Continued*

B. Properties requiring areal measurement (planimetry)—*Continued*

Property	Recommended symbol	Where used or defined	How derived	Units	Dimensions
Stream frequency	F	Horton, 1945, p. 285	$F = N_u/A_u$	Number per mi.^{2}	L^{-2}
Texture ratio	T	Smith, 1950, p. 657	$T = N/P$	Number per mi.	L^{-1}
Basin circularity	R_c	Miller, 1953, p. 8	$C = \frac{\text{area of basin}}{\text{area of circle}}$	.....	0
Basin elongation ratio	R_e	Schumm, 1956, p. 612	$R_e = \frac{\text{diam. of circle}}{\text{basin length}}$	.....	0
C. Properties involving elevation differences (relief aspect)					
Stream channel slope	θ_c	Horton, 1945, p. 295 Strahler, 1952b, p. 1135 Schumm, 1956		Ft./mi., %, or degrees	0
Stream channel slope, segment of order u	θ_u	Horton, 1945, p. 295		Degrees	0
Stream channel slope ratio	R_s	Horton, 1945, p. 295	$R_s = \theta_u/\theta_{u+1}$	.....	0
Ground slope, orthogonal to contour	θ_g	Horton, 1945, p. 305 Strahler, 1950		Degrees	0
Ground slope (valley - side slope), maximum angle of	θ_{max}	Strahler, 1950 Schumm, 1956 Melton, 1957		Degrees	0
Ratio of channel slope to ground slope	R_{cg}	Horton, 1945, p. 349	$R_{cg} = \theta_c/\theta_g$	.....	0
Dihedral angle between valley sides	ζ	Melton, 1957		Degrees	0
Relief, maximum in basin	H	Strahler, 1952b, p. 1119 Schumm, 1956 Melton, 1957		Feet	0
Relief ratio	R_h	Schumm, 1956, p. 612	$R_h = H/L_b$	.....	0
Relative relief	R_{hp}	Melton, 1957	$R_{hp} = H/P$	.....	0
Relative basin height (in hypsometry)	y	Strahler, 1952b, p. 1119–1121	$y = h/H$	.....	0
Relative basin area (in hypsometry)	x	Strahler, 1952b, p. 1119–1121	$x = a/A$	.....	0
Hypsometric integral	..	Strahler, 1952b, p. 1119–1121	$\int_0^{1.0} x\,dy$	.....	0
Volume of landmass	V	Strahler, 1952b, p. 1120–1121		Ft.^{3} or Mi.^{3}	L^3
Curvature of slope profile	K	.....		Radians per ft.	L^{-1}

In general, angular measurements in degrees are designated by Greek letters with lower-case subscripts. Ratios formed by two properties of identical dimension are designated by R with appropriate lower-case subscripts referring to the properties involved.

A horizontal bar above any term (*e.g.* $\overline{L_u}$) denotes a mean value and can be added to any of the above terms.

Symbols suggested here are not necessarily used by authors of the papers cited. Instead, some symbols are proposed here for the first time. Horton's use of a script letter o for order and l for length resulted in confusion of these letters with the numerals 0 and 1. Use of u for order follows Melton (1957).

Landform Dimensions

The first step in applying dimensional analysis to any field of physical geology is the assignment of a dimension to each important geometrical attribute of the body or material under consideration. Geomorphologists are concerned with the geometry of the land surface. Many of the form elements have the simple dimension of length, designated by the symbol L. Length of slope, length of a stream of a given order, and basin perimeter are obvious examples. Relief, defined as difference of elevation between summit and valley floor, also has the dimension of length.

Other form elements have the dimension of square of length, L^2. An example is area of drainage basin, because area is defined as the product of length and width; *i.e.*, the product of two length dimensions. Any volume measure has the dimension of length cubed, L^3, by definition of measure of volume.

In a different dimensional class are those form elements which are dimensionless, for which the conventional symbol is 0. Mathematically, this means that the fundamental dimensions are raised to the zero power and therefore equal unity. One important class of dimensionless elements is angle measurement. Angle of slope, angle of stream entrance, and stream azimuth are examples. This is explained through trigonometry. The definition of angle of ground-surface slope, measured on a straight line between two points, is that angle whose tangent is the vertical distance of rise divided by horizontal distance. Both vertical and horizontal distances have the dimensions of length, hence

$$\text{tan of slope angle} = \frac{\text{vertical dist.}}{\text{horizontal dist.}} \overset{d*}{=} \frac{L}{L} \overset{d}{=} 0.$$

Angular measure is dimensionless because two similar triangles must have the corresponding angles equal, whereas the lengths of the sides and the area enclosed can differ greatly.

Another important class of dimensionless form elements is composed of combinations of dimensional elements, the sum of whose exponents is zero. For example, the length-width ratio of a drainage basin is defined as length divided by width (or *vice versa*). Dimensionally,

$$\frac{\text{length}}{\text{width}} \overset{d}{=} \frac{L^1}{L^1} \overset{d}{=} L^{(1-1)} \overset{d}{=} 0$$

Another example is drainage-basin circularity in which

$$\text{Circularity} = \frac{\text{Basin area}}{\text{Area of circle of same perimeter}} \overset{d}{=} \frac{L^2}{L^2} \overset{d}{=} L^{(2-2)} \overset{d}{=} 0$$

Thus, any ratio is dimensionless which has the same dimension in the numerator as in the denominator. Obviously, a dimensionless number can express a form quality which is independent of the linear scale of the objects measured and consequently has great value in comparing forms of greatly differing dimensions.

Still another class of landform dimensions is that in which the dimension is the inverse of length. This dimension may be written as $\frac{1}{L}$ but is more conveniently stated in the exponential form L^{-1}. An example is drainage density, in which

$$\text{Drainage density} = \frac{\text{total stream length}}{\text{area of drainage basin}} \overset{d}{=} \frac{L}{L^2} \overset{d}{=} L^{(1-2)} \overset{d}{=} L^{-1}$$

Table 1 lists geometrical properties of landforms and cites references to definitions or applications of each. Other measures may be devised to suit the needs of particular investigations.

Table 2 summarizes the dimensions of various kinematic and dynamic quantities important in geomorphology, particularly with reference to fluvial erosional processes. Being concerned with motion, periodicity, or forces, the factors involve, in addition to a length dimension, the dimensions of mass, or time, or both. Convenient tables, accompanied by explanations of dimensional analysis of velocity, acceleration, force, stress, mass rate of flow, viscosity, and other basic dynamic terms, are given by Rouse (1938, p. 11) and Murphy (1949, p. 8).

If it served no other purpose than clarifying the essential nature of the elements measured, dimensional analysis would be a valuable research tool; but analysis of the dimensions is merely the first step in two important operations discussed below: (1) The formulation of rational equations through the Pi Theorem.

* The lower case d above the equal sign is used in this paper to designate the expression "dimensionally equal to" or "dimensionally equivalent to." Duncan (1953) has introduced as a new symbol for this purpose a capital D with a double bar, rotated 90° anticlockwise, but this may prove awkward in typing and typesetting. Dodge and Thompson (1937, p. 2) use the symbol $\approx$, a double similarity symbol, to denote dimensional equality.

TABLE 2.—KINEMATIC AND DYNAMIC PROPERTIES ASSOCIATED WITH EROSION PROCESSES ON WATERSHED SLOPES

Property	Symbol	Dimensional properties or definition	Dimensional symbol
Erosion intensity (Horton, 1945)	E_a, e_r	(a) Mass rate of removal per unit area	$ML^{-2}T^{-1}$
		(b) Volume rate of removal	L^3T^{-1}
Runoff intensity (Horton, 1945)	Q, q_s	(a) Mass rate of flow per unit cross section	$ML^{-2}T^{-1}$
		(b) Discharge; volume per unit time	L^3T^{-1}
		(c) Volume rate of flow per unit area of cross section	LT^{-1}
Rainfall intensity (Horton, 1945)	i	(a) Mass rate of flow per unit cross section	$ML^{-2}T^{-1}$
		(b) Discharge	L^3T^{-1}
		(c) Volume rate of flow per unit area of cross section	LT^{-1}
Infiltration capacity (Horton, 1945)	f	(a) Mass rate of flow per unit cross section	$ML^{-2}T^{-1}$
		(b) Discharge	L^3T^{-1}
		(c) Volume rate of flow per unit area of cross section	LT^{-1}
Eroding stress (Horton, 1945)	F_1, F_o	Force per unit area	$ML^{-1}T^{-2}$
Resistivity of surface (Horton, 1945)	R_i, R_1	Force per unit area	$ML^{-1}T^{-2}$
Energy expended per unit area in overland flow (Horton, 1945)	e	$\frac{\text{Force} \times \text{distance}}{\text{Area}}$	MT^{-2}
Velocity of overland flow	v	Distance per unit time	LT^{-1}
Erosion proportionality factor (Horton, 1945)	k_e	e_r/F_1	$L^{-1}T$
Depth of overland flow	δ, d	Length	L
Roughness (absolute)	k	Length	L
Unit weight of runoff (Horton, 1945)	w	Weight per unit volume	$ML^{-2}T^{-2}$
Viscosity (absolute)	μ		$ML^{-1}T^{-1}$
Viscosity (kinematic)	ν	μ/ρ	L^2T^{-1}
Density of fluid	ρ	Mass per unit volume	ML^{-3}
Acceleration of gravity	g	Distance per unit time, per unit time	LT^{-2}

(2) The investigation of geometric, kinematic, and dynamic similarities of natural systems.

DIMENSION SPACE

A graphic device by means of which dimensional properties and products may be readily visualized in geometrical terms is dimension space, or simply D space, introduced by Corrsin (1951, 1953). Figure 1 shows dimension space as it applies to classical mechanics, in which three fundamental physical dimensions—mass, length, time—suffice to define any physical quantity. These dimensions are represented by three orthogonal coordinate axes: length on the vertical axis; time on the horizontal axis from left to right; mass on the normal horizontal axis.

Coordinates are scaled in units from the origin, both positively and negatively, indicating the power, or exponent, to which the dimension is raised. Thus the point labeled +2 on the length scale represents L^2; the point -3 is L^{-3} or $1/L^3$. The origin of the coordinate system, labeled 0, represents dimensionlessness, or the nondimensional property, where the three dimensions are raised to the zero power.

Within this D space, each physical quantity in the realm of geomorphic processes and forms is a vector drawn from the origin to a point appropriate to its dimensions.

Figure 2 illustrates the length properties in

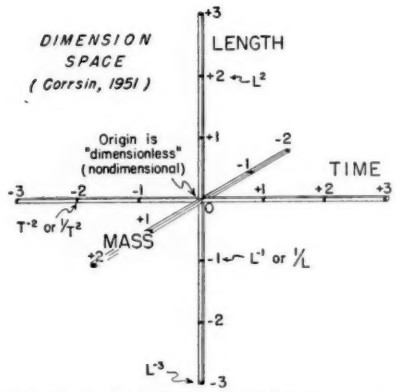

FIGURE 1.—DIMENSION-SPACE COORDINATES

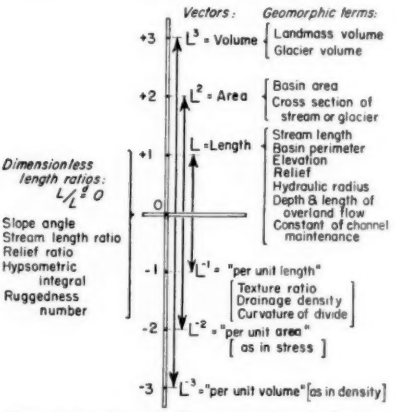

FIGURE 2.—LENGTH PROPERTIES IN D-SPACE

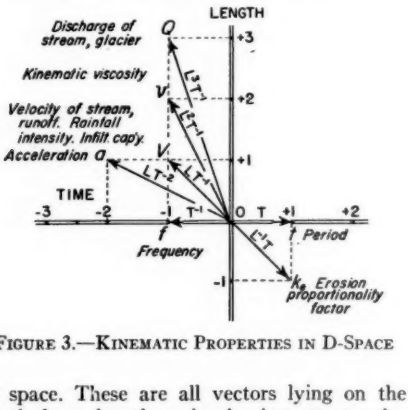

FIGURE 3.—KINEMATIC PROPERTIES IN D-SPACE

D space. These are all vectors lying on the vertical, or length, axis. An important principle of quantitative geomorphology is that the geometrical properties, or shapes, of landforms are wholly accommodated by length dimensions, or by dimensionless ratios of lengths. Form alone is static and has no substance; hence no time or mass dimensions.

Representative examples of length properties are listed on the right in Figure 2; on the left are examples of dimensionless numbers formed of length ratios. All angles and azimuths (such as dip and strike) are in this category, which, in general, expresses morphology, or shape, independently of scale or size.

Figure 3 introduces the time dimension in combination with length to yield kinematic properties lying in one plane of D space. Vectors of frequency and period lie along the time axis because they involve no distance. Velocity, acceleration, kinematic viscosity, and discharge (as volume rate of flow) lie in the upper left quadrant, but no usable physical properties are known for the upper right and lower left quadrants. In the lower right quadrant lies Horton's erosion proportionality factor, explained below. It is the inverse of velocity and is hence opposite and equal to the velocity vector.

Physical quantities involving mass, as well as length or time, or both, are designated as mechanical properties in Figure 4. All quantities shown are well known in mechanics and hence are frequently encountered in study of geomorphic processes.

Figure 5 illustrates dimensionless numbers in D space. Significance of each is treated below. Where three or more terms constitute the dimensionless number, it is represented by a closed vector circuit attached to the origin, as in the Froude and Reynolds numbers. Where two terms constitute the number, it may be represented by equal but opposite vectors in D space, as in the Horton number and landform geometry number shown on the right in Figure 5.

Dimension space is particularly helpful in explaining dimensional analysis to geologists, who are generally skilled in three-dimensional visualization of structural and crystallographic forms. A D space model constructed of wires or dowels is useful in classroom instruction on dimensional analysis.

METHOD OF DIMENSIONAL ANALYSIS IN FORMULATION OF RATIONAL EQUATIONS

In quantitative investigations of geomorphic processes and resultant forms, the relation-

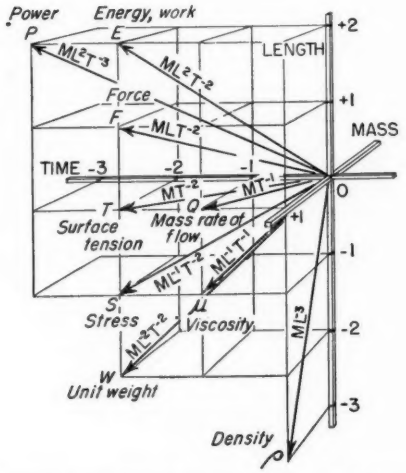

FIGURE 4.—MECHANICAL PROPERTIES IN D-SPACE

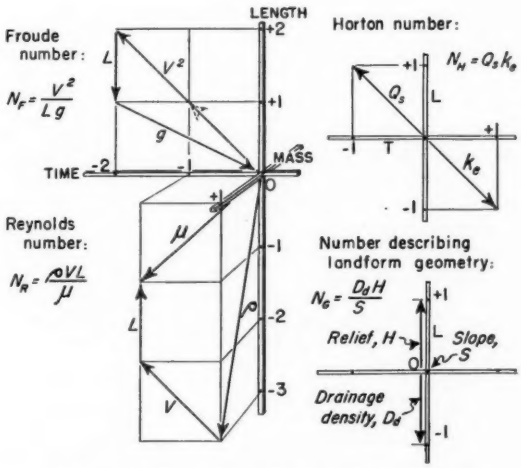

FIGURE 5.—DIMENSIONLESS NUMBERS IN D-SPACE

ships between the form elements or morphology and the causative factors need to be expressed by equations wherever possible (Strahler, 1952a). One important use of dimensional analysis is to determine the validity of an equation with respect to the fundamental units of mass, length, and time. When these units are so disposed as to equate dimensionally as well as numerically, the equation is said to be dimensionally homogeneous (Corrsin, 1953, p. 7–8). For example, an equation which defines discharge is

$$Q = AV \tag{1}$$

where

Q is discharge in cubic feet per second (c.f.s.).
A is cross-sectional area of channel in square feet.
V is mean velocity of flow in feet per second.

Analyzing each term dimensionally,

Q = volume per unit time $\stackrel{d}{=} L^3T^{-1}$

A = length x length $\stackrel{d}{=} L^2$

V = distance per unit time $\stackrel{d}{=} LT^{-1}$.

Substituting these dimensions in equation (1)

$$L^3T^{-1} \stackrel{d}{=} (L^2)\ (LT^{-1})$$

or

$$L^3T^{-1} \stackrel{d}{=} L^3T^{-1}$$

Because the products of dimensions on two sides of the equation are the same, the equation is said to be dimensionally correct.

Drainage density, the dependent variable, is considered first. In setting up the analysis, it is desirable to follow the dependent variable with those variables which can be regulated by experiment, or whose values can be observed through a natural range (Langhaar, 1951, p. 38–39). One of these is runoff intensity, Q, which is the difference between two of the major factors controlling drainage density:

TABLE 3.—DIMENSIONS OF VARIABLES IN DRAINAGE DENSITY EQUATION

Symbol	Term	Dimensional quality	Dimensional symbol
D	Drainage density (Horton)	Length divided by area	$\frac{L}{L^2} = L^{-1}$
Q	Runoff intensity (Horton)	Volume rate of flow per unit area of cross section	$\frac{L^3T^{-1}}{L^2} = LT^{-1}$
k_e	Erosion proportionality factor (Horton)	Mass rate of removal per unit area divided by force per unit area	$\frac{ML^{-2}T^{-1}}{ML^{-1}T^{-2}} = L^{-1}T$
H	Relief	Length	L
ρ	Density of fluid	Mass per unit volume	ML^{-3}
μ	Viscosity of fluid (absolute)		$ML^{-1}T^{-1}$
g	Acceleration of gravity	Distance per unit time, per unit time	LT^{-2}

More important than merely demonstrating the dimensional homogeneity of an existing equation is the use of dimensional analysis in setting up a dimensionally correct basic form of an equation relating a group of variables.

For illustration, a problem of particular interest to geomorphologists is the relationship of the factors which control drainage density. From data obtained by Smith (1954, Ph.D. thesis, Columbia University), Miller (1954), and Strahler (1952b), it is known that drainage density, defined by Horton (1945, p. 283) as length of stream channel (miles) per unit area (square miles), has an extremely wide range of values. Densities range from as low as 2–3 miles per square mile in regions of massive sandstones, to extreme values of 500–1000 or more for badlands in weak clays. From field observation and deduction, a list of controlling factors has been developed to explain these variations. An equation expressing the relationship of the most basic variables involved is developed from an initial equation stated as follows:

$$D = f(Q, k_e, H, \rho, \mu, g). \tag{2}$$

These terms are explained and dimensionally analyzed in Table 3.

rainfall intensity and infiltration capacity. Both are expressed in inches per hour, derived dimensionally from the full definition as discharge per unit area of ground surface ($L^3T^{-1}/L^2 \stackrel{d}{=} LT^{-1}$). Runoff intensity, Q, thus has the dimensions of a velocity. The third variable is an erosion proportionality factor, k_e, defined by Horton (1945, p. 324) as the ratio of erosion intensity to eroding force:

$$k_e = \frac{e_r}{F_1} \tag{3}$$

where

e_r = mass rate of erosion per unit area
F_1 = eroding force per unit area.

The erosion proportionality factor, k_e, expresses the resistance of the ground surface to erosion by surface runoff. It gives the quantity of material entrained from a unit area of surface when a particular eroding force is applied. For soft, incoherent materials such as silt or fine sand, this factor will be high; for hard rock surfaces or heavily vegetated soil surfaces, this factor will be low. It is well known that drainage density is high in badlands, where the rock is weak and unprotected by vegetative cover; low in regions of massive, strong bedrock and in heavily forested regions.

The fourth variable, relief, is also one which can be regulated through selection of the area of study. Relief may be measured in different ways, but it is most meaningful when measured as local relief, the difference in elevation between the summit point and mouth of a basin of first or second order (Table 1). Regions of great local relief normally have steep stream gradients and steep valley wall slopes, whereas regions of low relief normally have both gentle stream gradients and gentle ground slopes. Relief is also a function of stage of development in the erosion cycle and is therefore a function of time. It has been generally supposed that drainage density reaches a maximum in the early mature stage when relief is greatest but diminishes to lower values in late maturity and old age.

The variables, density and viscosity, are significant properties of the fluid and are included because the drainage system is developed by water erosion on slopes and in channels. The last variable, acceleration of gravity, represents the field of force in which the entire system operates. It will be noted that the first four variables involve no mass dimension, hence an analysis limited to these four would include only geometric and kinematic factors (length and time). To include a study of the forces acting in the system, the dimension of mass must be introduced, and this is present in both density and viscosity. Furthermore, if scale models are to be used and the dynamic similarity of the systems maintained, the force relationships must be maintained in certain ratios, discussed below.

Although an explanation of the terms is not essential to the development of the mathematical relationships, it is of prime importance scientifically. The variables must be selected with great care, to make certain that no important factors have been omitted, and that a real mechanism relates each independent variable with the dependent variable (Langhaar, 1952, p. 14–15).

The variables of equation (2) may be grouped into the functional relationship

$$f'(D, Q, k_e, H, \rho, \mu, g) = 0 \tag{4}$$

The number of variables in this function may be reduced to a smaller number of dimensionless products by application of the Pi Theorem, commonly ascribed to Buckingham (1914) and explained at length by Rouse (1938, p. 13–24), Langhaar (1951, p. 29–46), Corrsin (1951), and Duncan (1953, p. 87–98). Buckingham's Pi Theorem states that if a dependent variable, A_1, is related to the independent variables $A_2, A_3, \cdots A_n$, and to no others, so that the general functional relationship $A_1 = f(A_2, A_3, \cdots A_n)$ may be written as $f'(A_1, A_2, A_3, \cdots A_n) = 0$, and further, that these n physical quantities involve k physical dimensions, then there also exists a relation $\varphi(\pi_1, \pi_2, \pi_3, \cdots \pi_{n-k}) = 0$ in which each π term is a dimensionless product made up of the A's. Each π term contains $k + 1$ variables, and k variables are common to all π terms.

In the case at hand, there are seven variables and three fundamental dimensions; therefore, four dimensionless π terms will result:

$$\varphi(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \tag{5}$$

Solution of the four π terms, explained in the Appendix, yields:

Solution 1: $\pi_1 = \dfrac{1}{HD}$,

or $\dfrac{1}{\pi_1} = HD$ (Ruggedness Number)

Solution 2: $\pi_2 = \dfrac{1}{Qk_e}$,

or $\dfrac{1}{\pi_2} = Qk_e$ (Horton Number)

Solution 3: $\pi_3 = \dfrac{HQ\rho}{\mu}$ (Reynolds Number)

Solution 4: $\pi_4 = \dfrac{Q^2}{Hg}$ (Froude Number)

Before combining the four solutions into one equation, the meaning of each dimensionless product may be considered. Under Solution 1, there resulted HD, the product of relief and drainage density. It is purely geometrical in dimensional components and suggests steepness of slopes implicitly. If D should be increased while H remains constant, the average distance from divides to adjacent channels is reduced, with an accompanying increase in slope steepness. If H is increased while D remains constant, the elevation difference between divides and adjacent channels will also increase, so that steepness of slope will increase. Extremely high value of the ruggedness number occurs when both variables are high, that is, when slopes are not only steep but long as well.

Under Solution 2, a dimensionless product of runoff intensity, Q, and the erosion proportionality factor, k_e, is obtained, and this is here designated the Horton number, after Robert E. Horton (1945), who first explained these two variables in a geological publication. The Horton number is an indicator of the intensity of erosion on the slopes of a drainage basin, for, if either variable increases, a greater quantity of material will be expected to be taken from the slopes per unit time. An increase in runoff intensity will occur if either the rainfall intensity increases or the infiltration rate decreases. An increase of the erosion proportionality factor will be found in a change from a resistant ground surface to a weaker one, from which the particles are more easily entrained under a given eroding force.

Under Solution 3, the dimensional product is readily recognized as the Reynolds number, which is more commonly seen in the form

$$\mathbf{R} = \frac{\rho V d}{\mu} \tag{6}$$

where V is velocity of flow and d is diameter of a pipe, or depth of a stream. In Solution 3, the term V is replaced by Q, which has the dimensions of velocity; d is replaced by H, which has the dimension of length.

This substitution is permissible because the velocity term in the Reynolds number refers in general to any characteristic velocity in the system, whereas the length term refers to any characteristic linear dimension in the system. If two mechanical systems are to possess complete similarity, they must have the same Reynolds number. Although this number can be computed with respect to various characteristic velocities or lengths in the systems, the comparison of numbers of two systems is meaningful only when the terms are similarly defined in both. A Reynolds number for a drainage system might be made by using the length term drainage density, D, which would yield

$$\mathbf{R} = \frac{Q\rho}{D\mu} \tag{7}$$

Under Solution 4, the dimensional product is recognizable as the Froude number, which is perhaps more commonly seen in the form

$$\mathbf{F} = \frac{V^2}{dg} \tag{8}$$

in which V is the velocity of the fluid and d is the diameter of pipe or depth of stream. Here, as in the Reynolds number in the present solutions, runoff intensity, Q, is substituted for velocity; relief, H, for diameter or depth. The Froude number measures the ratio of forces of inertia to forces of gravity:

$$\mathbf{F} = \frac{\text{Force of inertia}}{\text{Force of gravity}}$$

To clarify this ratio, it should be noted that the mass terms necessary to define force (Mass times acceleration) have canceled out from both numerator and denominator. The inertial force in the numerator is represented by $\frac{V^2}{d}$, which has the dimensions of acceleration. $\left(\frac{L^2T^{-2}}{L} = LT^{-2}\right)$ The force of gravity is represented in the denominator by g, which is by definition an acceleration. As in the Reynolds number, the velocity term may be any characteristic velocity in the system; the length term any characteristic length. If two mechanical systems are similar dynamically, the Froude numbers (as well as the Reynolds numbers) will be the same for both, provided that the velocity and length terms are similarly defined in both systems.

The four dimensionless groups obtained by the four solutions may be combined as follows:

$$\phi\left(\frac{1}{\pi_1}, \frac{1}{\pi_2}, \pi_3, \pi_4,\right) = \phi\left(HD, Qk_e, \frac{Q\rho H}{\mu}, \frac{Q^2}{Hg}\right) = 0 \tag{9}$$

Solving for D,

$$D = \frac{1}{H} f\left(Qk_e, \frac{Q\rho H}{\mu}, \frac{Q^2}{Hg}\right), \tag{10}$$

Thus, drainage density is inversely proportional to local relief times a function of the Horton, Reynolds, and Froude numbers. From equation (2), with drainage density as a function of six variables, the number of independent variables to which values must be assigned by observation or controlled experimentation has been reduced to three in equation (10). Note that the reduction in number of independent variables is three, equal to the number of different dimensions represented (M, L, and T). In addition to simplifying the planning and organization of experiments and field observations, by reduction to dimensionless groups, "... dimensional analysis establishes the conditions for the validity of

experiments on models and the 'laws of comparison' of models with their prototypes." (Duncan, 1953, p. 121) In nature, landform systems of different scales of size occupy the relative positions of model and prototype in conventional engineering applications.

which are of different size. Basins A and B are said to be homothetic (Duncan, 1953, p. 14–20) because any two corresponding points in the basins lie on the same radius vector from a center of similitude, *i.e.*, are colinear. The points Q' and Q mark the mouths of the

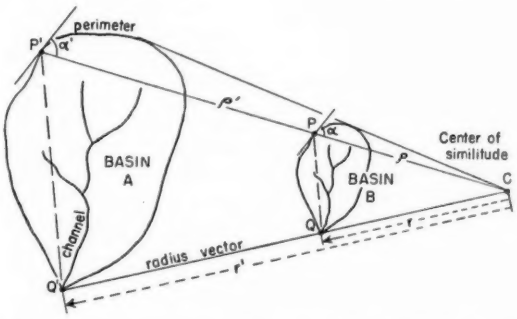

FIGURE 6.—GEOMETRICAL SIMILARITY OF TWO DRAINAGE BASINS

GEOMETRICAL SIMILARITY OF LANDFORMS

Systems of landforms involving the same geologic processes and materials are generally recognized to possess a considerable degree of similarity. Indeed, the basis of landform classification depends upon this. Glaciers are generally similar to one another; dunes to other dunes; beaches to other beaches, and so forth. Consequently, a quantitative consideration of similarity and how it may be measured is an important part of geomorphology.

Similarity of two systems (as for example, two dunes, two volcanoes, or two drainage basins) is complete when two phases of similarity are demonstrated (Murphy, 1949, p. 31–36):

(1) geometrical similarity, in which the shapes correspond, and
(2) dynamical similarity, in which all forces in the system are proportional. Special cases of dynamical similarity are
   (a) mechanical similarity, in which weight and density correspond, and
   (b) kinematical similarity, in which the two systems are similar at all corresponding times, or have the same periodicity of occurrence.

Consider geometrical similarity in two landform systems. Figure 6 shows the outline of two drainage basins which have the same shapes of outline and channel system, but basins; at corresponding distances r' and r from the center of the similitude. Two other corresponding points are P' and P, colinear and located at distances ρ' and ρ respectively from the center of similitude. For reasons self-evident from considerations of Euclidean geometry of similar triangles

$$r' = \lambda r \quad \text{and} \quad \rho' = \lambda \rho$$

where λ is the *linear scale ratio*. Consequently,

$$\frac{r'}{r} = \lambda = \frac{\rho'}{\rho},$$

which is to say that the radius vectors of any two colinear points are always in the ratio λ. It follows from the laws of similar triangles that the distances $P'Q'$ and PQ would also be related by the ratio λ. Hence, in two geometrically similar landforms, the distances between corresponding points in the system have the same scale ratio.

As applied to scale-model studies, the ratio λ is taken as the ratio of length in the prototype to length in the model and is therefore normally larger than unity. In landform analysis, the ratio of the larger to the smaller systems will be used, as both are natural landforms.

In geometrical similarity, the tangents to corresponding points on curved lines in the two systems are always equal. In Figure 6, the tangents of α' and α at the points P' and

P are equal. On the other hand, the degrees of curvature at corresponding points on the two figures are inversely related to the scale ratio as follows:

$$\frac{\text{Curvature at } P'}{\text{Curvature at } P} = \frac{1}{\lambda}$$

Ratios of corresponding areas between two geometrically similar systems are related by the square of the scale ratio as follows:

$$\frac{\text{Area of larger system}}{\text{Area of smaller system}} = \lambda^2$$

In Figure 6, the considerations of length and area have been based upon a two-dimensional figure, in which the relief features are projected upon a plane surface. If, however, the landform in its three dimensions is considered, corresponding volumes in two geometrically similar systems are related by the cube of the scale ratio as follows:

$$\frac{\text{Volume of larger system}}{\text{Volume of smaller system}} = \lambda^3$$

Using the above definitions and ratios, it may be concluded that two landforms are geometrically similar when all corresponding landform elements (Table 1) which have the dimension of length L are in the same ratio λ; when all corresponding measures having the dimension of inverse of length L^{-1} are in the scale ratio $\frac{1}{\lambda}$; and when those of dimension length-squared (L^2) are in the same ratio λ^2. Furthermore, all dimensionless properties 0 should have identical values in the corresponding parts of both systems. This means that the angle of slope and the tangents to all curved parts will be the same in the two systems.

Obviously, an absolute correspondence of all geometrical properties will not be found in nature. The ratio λ computed in various ways by measurement of corresponding parts will never be the same except by purest chance, but approximate similarity may exist.

In an attempt to test the concept of geometrical similarity in landforms, two regions of rugged terrain produced by fluvial erosional processes were compared. One area, which corresponds to the prototype, is in the Great Smoky Mountains. The data consist of the arithmetic means of various form element measurements from six representative small drainage basins in the Judson and Bryson, North Carolina, topographic quandrangles. The second collection of data consists of corresponding measurements from six basins in the Verdugo Hills in southern California. Further description of these areas is given elsewhere (Strahler, 1952b, p. 1131–1138). Table 4 gives a summary of similarity computations based upon mean length dimensions. On the right side of the table are shown the various values of λ based upon mean lengths of streams of first and second order, mean basin heights, and mean areas of basins of first and second order streams. Considering that the two regions are widely separated in climatic province and belong to regions of unlike tectonic history, the first five ratios might be viewed as remarkable for their similarity. The only value which is conspicuously different from the general run of the group is that of mean drainage basin heights of third-order streams. The low ratio of 1.17 indicates that the vertical dimension, or relief, of the topography is scaled somewhat differently from the other dimensions, which are all measured in the horizontal plane of the map onto which they are projected. This may lead to the conclusion that the slopes are steeper in the Verdugo Hills sample; and such is actually the case.

If geometrical similarity exists in the two areas being compared, dimensionless numbers can be expected to be identical in the two areas. A summary of this information is given in Table 5. One column gives the computed ratios; the right column evaluates the correspondence in purely subjective terms according to relative magnitude of observed differences. The correspondence is good to excellent in the first two comparisons, where only planimetric ratios (length ratios and bifurcation ratios) are involved. The correspondence of dimensionless ratios is also good for the hypsometric integrals, which are so consitituted as to neglect the factors of slope steepness and relief. The correspondence is only fair for maximum valley-wall slopes, which average a steeper value in the Verdugo Hills. Correspondence in ruggedness ratios and mean channel slopes is poor; in both instances, the number for the Verdugo Hills is almost double that of the Smoky Mountains. Without information on the sampling distribution of these ratios their differences cannot be evaluated statistically.

From these comparisons, a rather clear conclusion emerges: Geometrical similarity between the two regions is very closely achieved

TABLE 4.—COMPARISON OF LENGTH RATIOS IN TWO REGIONS

		Linear scale ratio
Mean length of 1st Order streams (L)		
Smoky Mtns.	$L_1 = 0.115$ miles	$\lambda_{L_1} = 1.85$
Verdugo Hills	$L_1 = 0.062$ miles	
Mean length of 2nd Order streams (L)		
Smoky Mtns.	$L_2 = 0.185$ miles	$\lambda_{L_2} = 1.59$
Verdugo Hills	$L_2 = 0.116$ miles	
Drainage density (L^{-1})		
Smoky Mtns.	$D = 14.16$ mi./sq. mi.	$\lambda_D = 1.85$
Verdugo Hills	$D = 26.17$ mi./sq. mi.	
Mean area of 1st Order basins (L^2)		
Smoky Mtns.	$A_1 = 0.01321$ sq. mi.	$\lambda_{A_1} = 1.86$
Verdugo Hills	$A_1 = 0.00383$ sq. mi.	
Mean area of 2nd Order basins (L^2)		
Smoky Mtns.	$A_2 = 0.0591$ sq. mi.	$\lambda_{A_2} = 1.71$
Verdugo Hills	$A_2 = 0.0203$ sq. mi.	
Mean basin heights (relief) of 3rd Order basins (L)		
Smoky Mtns.	$H = 1023.5$ ft.	$\lambda_H = 1.17$
Verdugo Hills	$H = 875.8$ ft.	

TABLE 5.—COMPARISON OF DIMENSIONLESS NUMBERS IN TWO REGIONS

		Dimensionless ratios	Degree of correspondence
Length ratios			
Smoky Mtns.	Ratio L_2/L_1	$= 1.61$	Good
Verdugo Hills	Ratio L_2/L_1	$= 1.81$	
Bifurcation ratios			
Smoky Mtns.	Mean of N_1/N_2 and N_2/N_3	$= 4.34$	Excellent
Verdugo Hills	Mean of N_1/N_2 and N_2/N_3	$= 4.45$	
Hypsometric integral			
Smoky Mtns.	Mean integral	$= 0.408$	Good
Verdugo Hills	Mean integral	$= 0.468$	
Ruggedness index			
Smoky Mtns.	$D \times$ relief	$= 1.45 \times 10^4$	Poor
Verdugo Hills	$D \times$ relief	$= 2.2 \times 10^4$	
Maximum valley-wall slopes			
Smoky Mtns.	Tan. of mean slope	$= 0.867$	Fair
Verdugo Hills	Tan. of mean slope	$= 0.990$	
Mean channel slopes			
Smoky Mtns.	Tan. of mean slope	$= 0.1233$	Poor
Verdugo Hills	Tan. of mean slope	$= 0.2246$	

where the planimetric data are compared on the planar projection of the topography upon a map surface. Thus planimetric similarity is perhaps demonstrated. On the other hand, those elements involving the third dimension, or relief, are not similar.

Two additional examples of similarity comparison illustrate two other types of results: a case in which six planimetric scale elements are remarkably similar; and a case in which the same six planimetric ratios showed great differences.

Table 6 lists the scale ratios for areas in western Virginia for which the morphometric data were gathered by V. C. Miller (1954), who gives a full description of the geomor-

phology and geology of these areas. In the first comparison, Column A, two apparently closely similar terrains are treated. The Blountville area is underlain by a sandstone facies of the Athens Formation; the Pennington area by ridge. We would not expect geometrical similarity between this belt and the area of dendritic drainage underlain by the Blountville Formation, and this is amply demonstrated by the data. Note that the

TABLE 6.—TESTS OF GEOMETRICAL SIMILARITY IN CLINCH MOUNTAIN REGION, VA.*

	A. Blountville vs. Pennington areas	B. Clinch Mtn. dip-slope vs. Blountville area
Scale Ratios		
Mean length of first-order streams	$\lambda_{L_1} = 1.06$	2.41
Mean length of second-order streams	$\lambda_{L_2} = 1.14$	3.09
Mean area of first-order basins	$\lambda_{A_1} = 1.15$	1.36
Mean area of second-order basins	$\lambda_{A_2} = 1.13$	1.96
Drainage density (first-order basins)	$\lambda_{D_1} = 1.24$	0.90
Drainage density (second-order basins)	$\lambda_{D_2} = 1.11$	1.11
Dimensionless Numbers		
Mean valley-side slopes	Blountville 31.8° Pennington 33.1	(No data)
Hypsometric integrals	Blountville 46.7% Pennington 54.4%	Blountville 47.6% Clinch Mtn. 48.4%
Circularity, R_c	Blountville 0.667 Pennington 0.664	Blountville 0.667 Clinch Mtn. 0.576

* Data from Victor C. Miller (1954).

interbedded shale and sandstone. Both areas have a uniform dendritic drainage pattern and appear to be relatively homogeneous within the limits of the areas sampled. It is not surprising, therefore, to find a close correspondence in all the length dimensions. The Blountville area has the larger dimensions in all cases, probably because the bedrock is more resistant to erosion, but the ratios are only slightly above unity. The mean angles of valley-wall slopes are nearly the same; a statistical test by Miller (1954) revealed no significant difference in the sample means. The hypsometric integrals appear to differ markedly but a statistical test indicates that this difference is not significant. Thus, the two areas compared in Column A of the table may be described as having approximate geometrical similarity in not only the planimetric aspects, but in the vertical dimension as well.

In Column B of the same table, the Blountville area dimensions are compared with those of drainage basins along the dip slope of Clinch Mountain (Miller, 1954). The effect of structural control has been to produce abnormally elongate drainage basins, arranged in roughly parallel order along the flank of the quartzite stream-length ratios are much higher than the area ratios. Thus, a glance at the list of ratios is sufficient to rule out geometrical similarity; and more than this, to indicate a strong dissimilarity.

Under rows of dimensionless number characteristics in Table 6, the hypsometric integrals in Column B are almost the same, but this is not of special value here because it has been found (Strahler, 1952b) that the integral is a highly stable property, remarkably little affected by other factors, once maturity of the drainage system is established. The circularity ratios, which are almost alike in Column A, are markedly different in Column B. This is to be expected, because the drainage basins on the flank of Clinch Mountain are drawn out into long, narrow ellipses.

Thus far, no attempt seems to have been made to inquire into the kinematical, mechanical, and dynamical similarity of drainage systems, although this offers a seemingly fruitful line of investigation into the very fundamentals of geomorphology. If approximate dynamical and geometrical similarity could be demonstrated, the kinematical relationships might be assumed to follow Froude's

Law of Time Scale (Murphy, 1949, p. 32) in which

$$\frac{t}{t_m} = \sqrt{\lambda}$$

where t and t_m are corresponding time intervals between similar events in two similar systems. If so, it might be possible to calculate from the observed rate of change of form elements in a rapidly eroded, small-scale system of badlands the rate of change of corresponding form elements in large-scale mountain masses. As with hydraulic scale models, perfect dimensional similarity cannot be achieved, if Reynolds and Froude numbers are required to be the same in prototype and model, unless the scale ratio is unity.

Theory of Drainage Density Transformations in Accelerated Erosion

Through the foregoing rational analysis, drainage density has been expressed as a function of relief and a Horton number. Also, morphometric analysis of drainage basins suggests that geometrical similarity tends to be preserved in planimetric aspect, but not necessarily in relief, or gradient aspect. Combining these deductions and observations, a general theory may be formulated for steady state development of erosion systems.

If, in equations (9) and (10), for purposes of further discussion the terms ρ, μ, and g are assumed to be nearly constant, the Reynolds and Froude numbers may be temporarily neglected, leaving

$$\phi(HD, Qk_e) = 0 \tag{11}$$

and

$$D = \frac{1}{H} f(Qk_e). \tag{12}$$

The dimensionless term of slope (ground surface or channel gradient in per cent), θ, is introduced into the ruggedness number. This can be done and still retain the nondimensional property of the number, whether θ is placed in the numerator or denominator. Considering that horizontal distance between divide and adjacent stream channel is equal to about half of the reciprocal of D (Horton, 1945, p. 284); that local relief, H, is a measure of vertical distance from stream to adjacent divide; ground slope, θ, will be defined as

$$\theta = H \cdot 2D$$

where θ is the tangent of the slope angle. Therefore

$$\frac{HD}{\theta} = \tfrac{1}{2}.$$

The quantities H, D, and θ, however, do not need to be defined as two sides and adjacent angle of the same triangle. Instead, consider H as any representative length property measured normal to the horizontal; D as any representative length property in the horizontal plane; and θ as some measure of slope representative of the mouthward-inclination of the watershed. For further discussion, let θ be used either as ground slope (mean of maximum valley-side slopes) or channel gradient (measured in first or second-order channels).

Whereas the ruggedness number, HD, as originally stated, ranges widely in numerical value, the modified number, HD/θ, which is henceforth called the geometry number, will tend to be conserved near unity throughout a wide range of drainage densities. High drainage density is normally compensated for by small local relief, H, and steep gradient, θ. Areas of lower drainage density commonly have greater local relief (*e.g.* long slope orthogonals) and gentler valley-side slopes and stream gradients. Table 7 shows rough estimates of HD and HD/θ for six localities differing greatly in drainage density. Despite a 120-fold range in D from locality No. 1 to locality No. 6, HD/θ has remained between 0.4 and 1.0.

Rewriting equation (11) with the geometry number gives

$$\phi\left(\frac{HD}{\theta}, Qk_e\right) = 0. \tag{13}$$

The geometry number can be regarded as a dimensionless group summarizing the essentials of landform geometry; the Horton number as a group summarizing intensity of the erosion processes.

Conditions of a steady state within a drainage basin are these: for a given Horton number, that is, for a given intensity of erosion process, values of local relief, slope, and drainage density reach a time-independent steady state, in which morphology is adjusted to transmit through the system the quantity of debris and excess water characteristically produced under the controlling regime of climate.

Consider next the changes produced by an

upset in the steady state. Suppose that a forested land surface is denuded of vegetative cover and intensively tilled. The Horton number will undergo a sharp increase, either through increase in runoff intensity or surface susceptibility, or both. In compensation, the first-order basin is outlined for comparison with the relatively large original basin and may be thought of as a small-scale model of the larger basin.

Plate 1, Figure 1 shows vividly the manner in which drainage density transformation at

TABLE 7.—ROUGH ESTIMATES OF RUGGEDNESS AND GEOMETRY NUMBERS, HD AND HD/θ FOR A WIDE RANGE OF CONDITIONS

Localities Arranged in Order of Increasing D

Locality	Drainage density (feet^{-1}) D	Relief (feet) H	Mean valley-side slope θ	Ruggedness number HD	Geometry number HD/θ
1. Gulf Coastal Plain (La.)	.0009	25	.06	.022	.38
2. Piedmont (Va.)	.0013	75	.17	.097	.57
3. Ozark Plateau (Ill.)	.0028	125	.54	.35	.65
4. Great Smokies (N. Car.)	.0028	300	.87	.84	.96
5. Verdugo Hills (Calif.)	.005	200	1.00	1.00	1.00
6. Perth Amboy Badlands (N. J.)	.12	6	1.10	.72	.66

Data for D and θ for localities 1–5 from Strahler (1952, Table 1); for locality 6 from Schumm (1956). Data for H estimated from topographic maps.

geometry is altered by gully development to increase drainage density greatly, to increase slope gradients (both ground and channel slopes) moderately, and to decrease the local relief (where measured as difference in summit and mouth elevations in the first-order basin).

When transformation is complete, a new set of forms very much smaller in linear scale replaces the original forms, while a new steady state of erosion is achieved on a much more intensive level. Thus, badlands, producing sediment at a high rate, come into being and will remain as long as surface conditions do not change and depth of erodible soil is adequate. These changes are shown schematically in Figure 7.

Given a first-order drainage basin and its single original channel (solid lines), the valley-side slopes leading down to the single channel will be long and smooth, as the profile indicates. When the Horton number is sharply increased by surface changes, rapid gullying ensues. Growth and subdivision of many new channels greatly increases the drainage density and creates many new stream segments of first, second, and third orders. A single small Ducktown, Tennessee, is causing badlands to replace smooth, sod-covered slopes.

As drainage density becomes great, local relief becomes small, where local relief is defined as the difference in elevation between summit and mouth of a first-order basin. The relief change is seen in profiles in the lower half of Figure 7. Slope, both of valley sides and stream channel gradients, has markedly increased as drainage density transformation has taken place. Steeper slopes permit the transportation not only of a greater quantity of bed load per unit time, but of larger particles as well. Aggradation of the main, axial channel of the watershed is therefore required to steepen its gradient to the point where this greater, coarser load can be moved. Valley-bottom alluviation is well known as an accompaniment to severe erosion on surrounding slopes (Happ, Rittenhouse, and Dobson, 1940, p. 92).

Ultimately, drainage-density transformation will produce a complete watershed system in which the geometrical similarity with the former system is preserved in horizontal aspect or plan view, but not in vertical aspect (since

PLATE 1.—EROSIONAL LANDFORMS NEAR DUCKTOWN, TENNESSEE

FIGURE 1.—Early stage in transformation of drainage density by progressive gullying.
FIGURE 2.—Drainage-density transformation completed.

FIGURE 1

FIGURE 2

EROSIONAL LANDFORMS NEAR DUCKTOWN, TENNESSEE

slopes are steepened). In some parts of the Ducktown area, transformation has progressed well on toward this limit (Pl. 1, fig. 2), although the vestiges of original forms are strongly apparent as envelopes over the new forms. Return to original scale might be anticipated if the surface were reforested, but otherwise the badland forms will persist until the weak material is removed and a highly resistant bedrock makes its appearance at the surface.

Referring back to the complete equation of four dimensionless groups (Equation 9), the effects of drainage density transformation upon the Reynolds and Froude numbers would be a marked increase in both. It is anticipated that the relative increase in runoff intensity, Q, would be greater than the relative decrease in relief, H, judging from the examples in Table 7, hence that the Reynolds number would rise. In the Froude number, the increase of Q as a square, combined with decrease of H in the denominator, would effect an enormous increase in the number as a whole. Thus the inertial force in the erosion system will increase appreciably over the viscous force and very greatly over the gravitational force, assuming that viscosity, density, and acceleration of gravity are nearly constant in nature.

Future research might profitably be directed toward determining quantitatively the relations among the four dimensionless groups over a wide range of natural conditions.

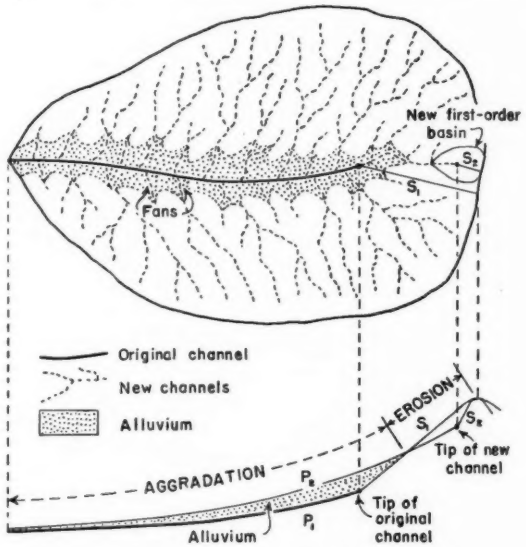

FIGURE 7.—DRAINAGE DENSITY TRANSFORMATION

CONCLUSION

Dimensional analysis will become increasingly useful in empirical, quantitative studies in geomorphology by offering a systematic means of describing and comparing the form elements of the landscape. By its application through the Pi Theorem, dimensional analysis facilitates the rational formulation of mathematical relationships and reveals dimensionless groups which characterize the critical relationships among variables. Studies of similarity, whereby the dynamics of geomorphic systems of greatly differing scales can be compared, requires dimensional analysis of all properties of the systems.

Using the Pi Theorem to reduce variables has facilitated the development of a general theory of fluvial erosion in terms of steady state systems in which geometry is adjusted to erosion intensity. This theory links together various observed phenomena of erosion and sedimentation into a unified process and will enable more complete predictions of form changes to be anticipated when watershed treatment is altered.

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Appendix. Solution of Pi Terms in Drainage Density Equation

Method of solution described here is taken from Rouse (1938, p. 13–18). For alternate method, *see* Langhaar (1951, p. 47–59).

The variables in Equation (2) were grouped into the functional relationship

$$f'(D, Q, k_e, H, \rho, \mu, g) = 0 \tag{4}$$

Because there are seven variables and three fundamental dimensions (M, L, T), there will result four Pi terms with three of the variables common to all four. Prior experience and the anticipation of the most useful dimensionless products indicate that the three common variables should be a characteristic length, H, the velocity term, Q, and the density term, ρ. The remaining variables are introduced in succession and for convenience are given the exponent -1. Thus we write

$$\varphi(\pi_1, \pi_2, \pi_3, \pi_4) = 0. \tag{5}$$

in which

$$\pi_1 = H^{x_1} Q^{y_1} \rho^{z_1} D^{-1}$$

$$\pi_2 = H^{x_2} Q^{y_2} \rho^{z_2} k_e^{-1}$$

$$\pi_3 = H^{x_3} Q^{y_3} \rho^{z_3} \mu^{-1}$$

$$\pi_4 = H^{x_4} Q^{y_4} \rho^{z_4} g^{-1}$$

In each solution, when the variables are replaced by corresponding products of M, L, and T, the sum of the exponents of each dimension must equal zero. Thus, three linear equations will be solved simultaneously for each Pi term, as follows:

Solution 1:

$$\pi_1\colon (L)^{x_1}(LT^{-1})^{y_1}(ML^{-3})^{z_1}(L^{-1})^{-1}$$

$$M\colon \quad z_1 \quad = 0$$

$$L\colon x_1 \quad +y_1 \quad -3z_1 \quad +1 = 0$$

$$T\colon \quad -y_1 \quad = 0$$

$$x_1 = -1, \quad y_1 = 0, \quad z_1 = 0.$$

$$\pi_1 = \frac{1}{HD} \quad \text{or} \quad \frac{1}{\pi_1} = HD$$

(Ruggedness number)

Solution 2:

$$\pi_2 = (L)^{x_2}(LT^{-1})^{y_2}(ML^{-3})^{z_2}(L^{-1}T)^{-1}$$

$$M\colon \quad z_2 \quad = 0$$

$$L\colon x_2 \quad +y_2 \quad -3z_2 \quad +1 = 0$$

$$T\colon \quad -y_2 \quad -1 = 0$$

$$x_2 = 0, \quad y_2 = -1, \quad z_2 = 0$$

$$\pi_2 = \frac{1}{Qk_e} \quad \text{or} \quad \pi_2 = Qk_e$$

(Horton number)

Solution 3:

$$\pi_3 = (L)^{x_3}(LT^{-1})^{y_3}(ML^{-3})^{z_3}(ML^{-1}T^{-1})^{-1}$$

$$M\colon \quad z_3 \quad -1 = 0$$

$$L\colon x_3 \quad +y_3 \quad -3z_3 \quad +1 = 0$$

$$T\colon \quad -y_3 \quad +1 = 0$$

$$x_3 = 1, \quad y_3 = 1, \quad z_3 = 1.$$

$$\pi_3 = \frac{HQ\rho}{\mu}$$

(Reynolds number)

Solution 4:

$$\pi_4 = (L)^{x_4}(LT^{-1})^{y_4}(ML^{-3})^{z_4}(LT^{-2})^{-1}$$

$$M\colon \quad z_4 \quad = 0$$

$$L\colon x_4 \quad +y_4 \quad -3z_4 \quad -1 = 0$$

$$T\colon \quad -y_4 \quad +2 = 0$$

$$x_4 = -1, \quad y_4 = 2, \quad z_4 = 0$$

$$\pi_4 = \frac{Q^2}{Hg}$$

(Froude number)

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CONTRIBUTION TO THE PETROGRAPHY OF THE TANNER GRAYWACKE[1]

BY REINHARD HELMBOLD
Translated by FRANKLYN B. VAN HOUTEN

ABSTRACT

(Prepared by the Translator)

Helmbold's detailed study of the classic upper Devonian-lower Mississippian Tanner graywacke of the Harz Mountains is based primarily on analyses of three spot samples from quarries near Scharzfeld.

Quantitative chemical analyses, petrographic description, and quantitative computation of principal constituents including estimates of mineral components of rock fragments, and measurements of sorting, shape, and orientation of grains are presented.

The Tanner graywacke is a hard, tough, poorly sorted gray-green sandstone containing the following constituents (average of three analyzed specimens in volume per cent): quartz—24.6, feldspar—32.1, rock fragments—23.0, and matrix—20. Source rocks that supplied these constituents are estimated as follows (average of three analyzed specimens in volume per cent): igneous rocks—58, metamorphic rocks—29, and sedimentary rocks—13.

The geologic setting, texture, composition, and sedimentary structures, such as graded bedding, indicate that the Tanner graywacke is a deposit of an orogenic belt, derived from the southeast, and deposited largely by periodic turbidity currents.

The poor sorting and poor rounding of the grains, the abundant feldspar and rock fragments, and the postulated mode of origin of the Tanner graywacke agree with qualitative specifications of other graywackes, but its quantitative composition deviates from published analyses of them.

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[1] Translated from Heidelberger Beiträge zur Mineralogie und Petrographie, 1952, Bd. 3, p. 253-288. From the Sedimentary Petrography Institute of Göttingen University.

The first six descriptive sections and the last three summary sections are translated closely. The analytical sections (VII–X) are summarized. Figures 1 and 2 have been added to the translation. The translator's notes are enclosed in brackets.

Headings are numbered or lettered as in the original to facilitate reference to it.

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I. Introduction

Since the early days of geology certain detrital sedimentary rocks have been called "graywacke". This kind of rock is so characteristic of British formations now assigned to the Paleozoic that the Cambrian, Silurian, and Devonian ones were designated the Graywacke Group in the 1832 edition of De La Beche's *A Geological Manual.* Graywackes are found in all parts of the world, and according to Krynine (1948, p. 153) they are "by far the most important kind of sandstone and are the most abundant single rock type within the sedimentary section". [Krynine was referring to low-rank graywackes, or subgraywackes, however, and not to the Tanner graywacke type of rock.]

Despite the fact that graywackes have been known for so long and are of world-wide distribution, there is still insufficient information about their petrography. This is partly due to the fact that this heterogeneous rock, whose grain size ranges from clay to gravel, cannot readily be quantitatively analyzed. Moreover, its unusual induration renders useless the ordinary petrographic methods applied to unconsolidated sediments.

As a consequence of the incomplete knowledge of graywackes very different kinds of detrital rocks have been so designated. Recently, Krynine (1948) and Pettijohn (1949) have published somewhat contradictory definitions and interpretations of graywacke as a rock type distinct from other kinds of detrital rocks. The present work does not propose a general definition, but aims instead to examine and describe thoroughly the rocks of the Harz Mountains (Fig. 1) that have long been called graywacke.

II. Brief Statement of the Geologic Setting

The Tanner graywacke extends across the entire Harz Mountains in a reverse S-shaped belt from the vicinity of Lauterberg and Scharzfeld in the southwest, through Tanne, to the vicinity of Gernrode in the northeast (Fig. 2). This so-called Tanner complex, which is a 500- to 1000-meter sequence consisting mostly of fine-grained graywacke, shale and argillite, and some chert, is tentatively correlated with the Acker-Bruchberg system at the Devonian-Carboniferous boundary (Schriel, 1928; 1939; Schwan, 1950). The youngest beds overlapped transgressively by the Tanner graywacke are the *Gonioclymenia* beds of the Dasberg stage [late Devonian], and the Tanner graywacke is in turn overlapped transgressively by the Kulm [Mississippian] cherts. A stratigraphic subdivision of the Tanner complex has not yet been made.

III. Location and Description of the Outcrops

The exposures from which the analyzed specimens were collected lie at the mouth of the Great Andreas Creek valley at Zoll near Scharzfeld, at the southwestern end of the belt of Tanner graywacke. The quarries are severely faulted and jointed. Commonly the fault planes are curved. Only two quarries were examined in detail (designated II and III in this investigation). In both (Fig. 3), beds a few centimeters to 120 cm thick and sharply separated from one another by thin shaly partings (2–10 cm) are succeeded by 10 m or more of massive graywacke overlain in turn by brittle and partly slabby argillite. The sequences in the two quarries do not correspond in every detail, however.

IV. Grain Size and Stratification

Of the 57 specimens from the entire profile of quarry II which were examined in thin section, 11 have a maximum grain-size range of fine gravel (up to 3.7 mm); 31 range up to very coarse sand (2.0 to 0.63 mm); and 15 to coarse sand (0.63 to 0.2 mm). The average of maximum grain size, 1.7 mm, is within the range of

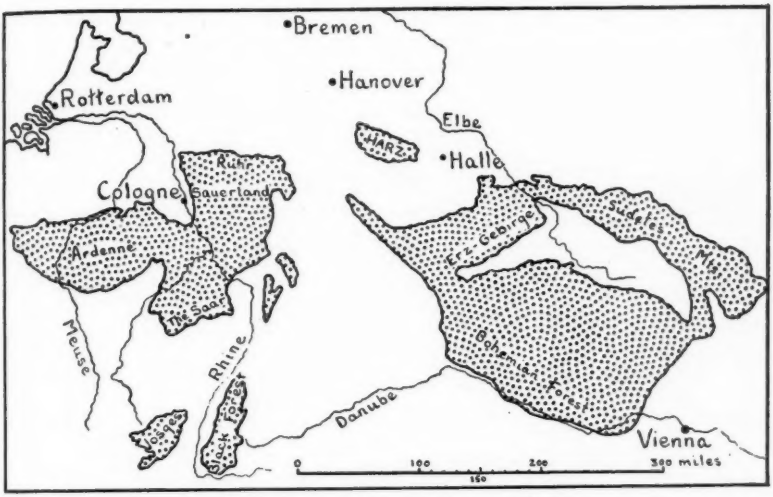

FIGURE 1.—SKETCH MAP OF CENTRAL EUROPE
Showing location of the Harz Mountains and other Hercynian massifs

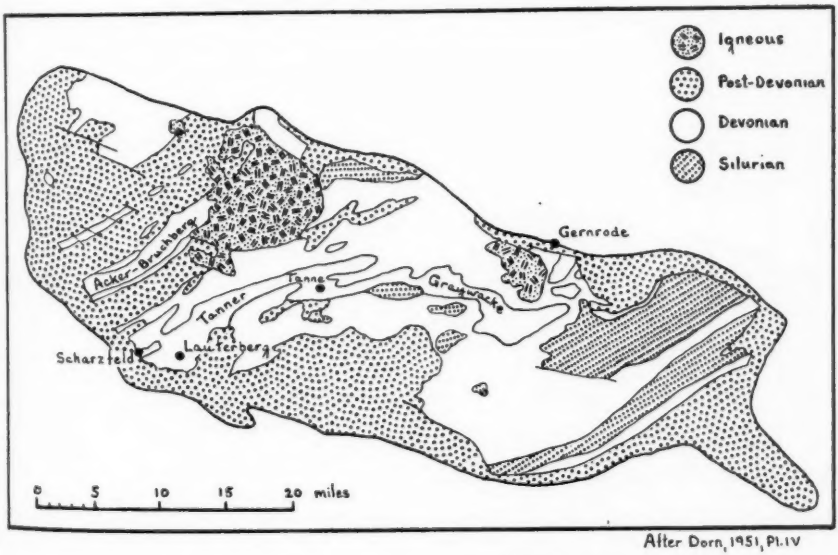

FIGURE 2.—GEOLOGIC MAP OF THE HARZ MOUNTAINS

very coarse sand. Calculated from the thickness of the beds, 19 per cent of the graywacke in quarry II has a maximum grain size of fine gravel, 56 per cent of very coarse sand, and 25 per cent of medium to coarse sand. [More commonly, grain size is described by its average, not its extreme, value. See Figure 4.]

Graded bedding of the sort recently discussed by Kuenen [and Migliorini] (1950) was observed in many layers but not in all. Graded bedding implies a change in maximum grain size within each layer. The differences in maximum grain size in the lower and upper parts of a bed commonly are considerable; for

example, in a bed 55 cm thick the maximum grain size in the lower part is 1.25 mm and in the upper part 0.25 mm. In almost every graded bed the grain size decreases from bottom to top. Nevertheless, in some thick beds (1–2 m)

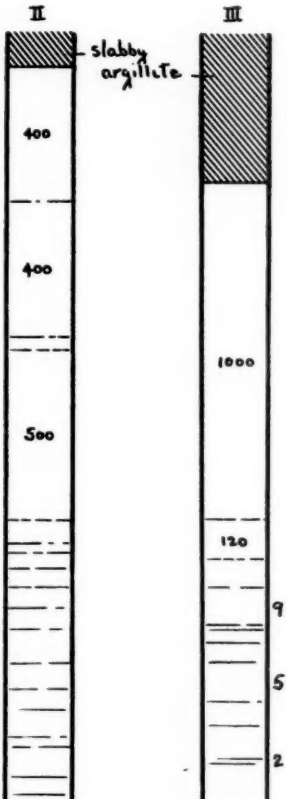

FIGURE 3.—SEQUENCE OF BEDS IN QUARRIES II AND III

Showing location of spot samples III 2, III 5b, and III 9b. II is 230 m thick, III is greater than 198 m thick. Thickness given is in centimeters.

the coarsest grain size occurs in the middle. Beds 4–5 m thick are even more irregular. They exhibit frequent change of maximum grain size, but the change is always gradational. In these beds the maximum grain size fluctuates between 0.5 and 3.5 mm.

The layers vary greatly in thickness and grain size. Commonly the thickest beds are also the coarsest-grained. Examined from bottom to top, the grain size within many of the layers reaches an average value just a few centimeters above the base, and this value remains constant to within a few centimeters of the overlying bed. Then it rapidly decreases to a minimum, (in places within a single thin-section). Other beds exhibit a nearly continuous gradation which is imperceptible on a small scale (as in a hand specimen).

V. MEGASCOPIC DESCRIPTION

The average Tanner graywacke from Scharzfeld is a compact gray-green rock of great hardness and resistance to shatter. Individual grains are scarcely recognizable megascopically. Weathering changes the color to red brown. In the very coarse-grained types one can recognize white quartz and feldspar, reddish porphyry, black slate, and other rock fragments. Especially in the coarse-grained beds, one finds shreds of slate or shale much larger than the other components. These twisted and irregular fragments commonly reach hand size; toward the top of a bed they are smaller, approaching the common grain size. Pettijohn (1949, p. 252) described similar shale or slate shreds and interpreted them as "the product of scour and subaqueous erosion of associated slates." Their existence is possible only because of very short transport. The generally jumbled arrangement and distribution in a layer suggests a turbidity current.

Many of the thin clay laminae in the beds are faintly ripple-marked. Moreover, the graywacke beds also occasionally exhibit distinct ripples.

The question of whether these actually are ripple marks cannot be answered unequivocally. The "wave length" averages about 7 cm. The ratio of wave length to amplitude fluctuates between 6 and 9. Generally the ripples are asymmetrical, suggesting current ripples.

In quarry II *Cyclostigma* remains, fossil leaves, and layers composed almost entirely of plant debris occur in the uppermost part of the section; these have already been described in many other reports.

VI. SAMPLING

In quarry II a complete profile was sampled; in quarry III samples were collected from the accessible thick-bedded layers. Inspection of some 60 thin sections indicates that classification according to grain size is the only feasible method. Therefore three principal grain-size

categories were selected for the exhaustive quantitative analysis: a medium-grained type that represents the average, an extremely fine-grained type, and a very coarse-grained type. ing and independent. Compared with microscopic analysis, which in the case of graywacke is loaded with many uncertainties, the chemical analysis is relatively reliable and thus serves as

TABLE 1.—CHEMICAL ANALYSES OF THE THREE SAMPLES INVESTIGATED

	Coarse-grained III 9b			Medium-grained III 5b		Fine-grained III 2	
	a	b	c	a	b	a	b
SiO_2	69.09	69.70	71.82	68.85	69.47	67.74	68.20
TiO_2*	0.99	0.998	1.03	0.74	0.75	0.69	0.70
Al_2O_3*	10.07	10.16	10.21	12.05	12.14	13.23	13.31
Fe_2O_3	2.57	2.59	2.67	2.72	2.74	3.12	3.14
FeO	1.33	1.34	1.38	2.03	2.05	2.24	2.25
MnO	0.06	0.06	0.06	0.05	0.05	0.05	0.05
MgO	4.01	4.05	3.51	2.96	2.98	2.91	2.93
CaO	1.48	1.49	0.62	0.50	0.50	0.52	0.52
Na_2O	3.87	3.91	4.06	4.87	4.91	4.25	4.27
K_2O	1.71	1.73	1.78	1.81	1.82	1.82	1.83
H_2O^+	2.34	2.36	2.36	2.30	2.32	2.49	2.51
H_2O^-	0.89	.....	.....	0.77	.....	0.74	.....
P_2O_5	0.06	0.06	0.06	0.06	0.06	0.05	0.05
CO_2	1.43	1.44	0.05	0.08	0.08	0.06	0.06
C	0.06	0.06	0.06	0.07	0.07	0.07	0.07
S	0.07	0.07	0.07	0.08	0.08	0.09	0.09
BaO	trace	.....	.....	trace	.....	trace	.....
Zn	0.0019	.....	.....	0.0010	.....	0.0033	.....
Cl	0.007	.....	.....	.....	.....	0.002	.....
Br	0.00000039	.....	.....	.....	.....	0.00000028	.....
	100.03	.....	.....	99.94	.....	100.07	.....
−O	0.02	.....	.....	0.02	.....	0.02	.....
Total	100.01	100.01	99.74	99.92	100.02	100.05	99.98
Density	2.68	.....	.....	2.68	.....	2.69	.....

a. Analysis with H_2O^-; b. analysis converted to material without H_2O^-; c. see discussion of analysis results. Where the sulfur occurs as sulfide (pyrite), an equivalent amount of oxygen must be subtracted from the analysis results. Zn was determined spectrographically by Karl Hans Wedepohl. Cl and Br were determined by Walter Behne.

* Corrected data from new analyses by Dr. Paula Schneiderhöhn, supplied by Dr. C. W. Correns (Personal communication to translator, 1955)

Inasmuch as the specimens from quarry II are more intensely weathered than those from quarry III, three oriented spot samples were selected from the least-complex and least-deformed part of quarry III. Sample III 2 was chosen as representative of fine-grained graywacke, sample III 5b as the medium-grained type, and sample III 9b as the coarse-grained type.

The quantitative chemical analysis of these samples is given first because it is self support- a control and—so far as seems feasible—as a basis for correcting the results of microscopic analysis.

VII. QUANTITATIVE CHEMICAL ANALYSIS

The analyses were made according to the procedure for rock analysis devised by Washington (1930) and Hillebrand (1919). The carbon determination followed the method Correns (1937) devised for the METEOR study. Alkali

determination was carried out according to Smith's method combined with flame-photometer determinations.

In order to make the analysis results more comparable, they were converted to material free of hygroscopic water, then adjusted to 100 per cent (Table 1, b). The analyses agree in general except for the remarkably high CO_2, CaO, and MgO content of sample III 9b. In addition there is a slight decrease in SiO_2 and a substantial increase in Al_2O_3, Fe_2O_3, and FeO from the coarser-grained to the finer-grained samples.

As far as possible the quantitative chemical and microscopic analyses were made on samples free of fractures filled with secondary minerals. This was easily achieved with samples III 2 and III 5b, but all the thin sections of sample III 9b are permeated with obscure fractures filled with dolomite, chlorite, and quartz. The graywacke itself has no carbonate except the minute calcite that occurs as an alteration product in some plagioclase. The high CO_2, CaO, and MgO content reveals that it was not possible to exclude the finer fractures in sampling the rock. The small amount of chlorite and quartz in these fractures does not noticeably affect the analyses because of the great amount in the graywacke itself, but the dolomite content of the fractures plainly modifies the results.

To make the chemical and microscopic analyses comparable the dolomite constituent was removed from the analyses. A 0.05 per cent CO_2 content was assumed for sample III 9b, and the remaining 1.38 per cent CO_2 was converted to dolomite which involves 0.86 per cent CaO and 0.50 per cent MgO. These amounts were then subtracted from the analysis results, and the corrected results are converted to 100 per cent (Table 1, c).

VIII. Microscopic Description of the Constituents

This section consists primarily of a petrographic description of the following constituents and a discussion of the basis for converting them to their chemical components and from volume per cent to weight per cent, and for determining the mineral components of the rock fragments:

1. Mineral grains: Feldspar, Quartz, Quartz-feldspar intergrowths, Chlorite, Mica, Limonitic material, Rare minerals.

2. Rock fragments: Acidic volcanic rocks, Intermediate and basic volcanic rocks, Acidic plutonic rocks, Chert, Shale and slate, Sandstone, Phyllite, mica schist, and chlorite schist, Micaceous or chloritic quartzite schist, Quartzite, Gneiss, Hornfels.

3. Fissure Minerals.

Only about 2–3 per cent of the feldspar grains in the three samples is clear and unweathered; most of this is orthoclase. Accordingly, 97–98 per cent of the feldspar is weathered and is counted as plagioclase. This approximation agrees with the chemical analyses. Of the plagioclase, 85–90 per cent is untwinned —predominantly albite ($An_{2\text{-}10}$); 10–15 per cent is twinned feldspar which is predominantly oligoclase-andesine ($An_{25\text{-}35}$). In converting the "total minerals" to their chemical components an average plagioclase composition of An_8 was assumed. At least 95 per cent of the plagioclase, which shows all stages of decomposition, has undergone advanced sericitization. Consequently a 10–15 per cent average sericite content of the plagioclase was used in making the chemical calculations.

IX. Quantitative Microscopic Determination of the Constituents

Following an explanation of a modified Rosiwal procedure, results of detailed microscopic determination of volume per cent (Table 2, a) based on counts of 100 grains in each of 14 size classes (3.56–<.002 mm) in the coarse-grained specimen and of 12 classes (2.–<.002 mm) in the medium and the fine-grained specimens, and a calculation of the principal constituents in weight per cent (Table 2, b) are presented in 17 tables with explanatory notes (summarized in Tables 2 and 3).

Volume per cent was converted to weight per cent by combining the mineral grains and minerals in rock fragments as "total minerals". These were then converted to their chemical components in which the sericite content of plagioclase was computed as muscovite. Because of possible error in values based on the microscopic analyses, the calculated constituents (Table 3, b) were corrected (Table 3, c) according to the results of the quantitative chemical analysis (Table 1, b and c). Final computation of the principal constituents of the Tanner graywacke in weight per cent is shown in Table 2, b. In computing these figures for mineral grains (omitting rare

minerals), the mineral composition of rock fragments (Table 3, a) has been subtracted from the corrected "total minerals" composition (Table 3, c), except that the sericite derived from feldspar has been subtracted from the mica content and converted again to feldspar. The figure for total rock fragments in the final computation (Table 2, b) is the sum of the mineral content of rock fragments (Table 3, a). The failure of these final figures (Table 2, b) to total 100 per cent results from the corrections made and from their conversion to weight per cent.

Assignment of the principal constituents to source rocks is summarized in Table 4.

The grain-size distributions of the principal constituents and of the whole samples are presented in histograms and cumulative curves. The principal constituents occur in the following order of decreasing average grain size: rock fragments, quartz and feldspar, chlorite, limonite, and mica. Grain-size distributions of the whole samples are discussed in the following section.

TABLE 2.—PRINCIPAL CONSTITUENTS OF TANNER GRAYWACKE
(Data from Tables 2, 5, 6, 7, 10, 11, 12, 15, 16, 17)

	Coarse-grained III 9b		Medium-grained III 5b		Fine-grained III 2	
	a	b	a	b	a	b
Mineral Grains						
Total quartz	25.29	26.10	23.98	23.96	24.57	24.38
Total feldspar	30.82	30.89	32.24	41.52	33.22	40.61
Mica	0.84	0.91	1.50	1.66	2.92	3.06
Chlorite	8.49	9.25	14.94	8.76	15.98	8.87
Limonitic material	3.37	2.91	7.84	3.09	4.14	3.12
Rare minerals	....	....	0.50	...	0.39	...
Total minerals	68.81	....	81.00	...	81.22	...
Rock fragments						
Acidic volcanic rocks	7.68	....	2.72	...	5.49	...
Intermediate and basic volcanic rocks	2.01	....	1.62	...	1.70	...
Acidic plutonic rocks	2.45	....	2.63	...	3.32	...
Chert	1.13	....	2.49	...	0.29	...
Shale and slate	3.53	....	2.02	...	1.08	...
Phyllite, mica, and chlorite schist	0.15	....	1.46	...	1.89	...
Micaceous quartzite schist	2.26	....	2.57	...	1.76	...
Chloritic quartzite schist	2.64	....	1.65	...	1.84	...
Quartzite	4.67	....	0.83	...	0.74	...
Sandstones	1.58	....	0.83	...	0.25	...
Hornfels	0.98	....	0.18	...	0.08	...
Gneiss	1.01	....	0.00	...	0.34	...
Total rock fragments	31.19	30.11	19.00	19.09	18.78	17.77
	100.00	100.17	100.00	98.08	100.00	97.81

(a) Microscopic count in volume per cent.
(b) Adjusted weight per cent calculated from data summarized in Table 3.

X. FABRIC (STRUCTURE AND TEXTURE)

1. Grain-size distribution, sorting, and packing

Grain-size distributions of the three samples studied (Fig. 4) are unimodal and appear normal. Moreover, they have a similar pattern except that the maximum shifts toward the coarse-grained fraction with increasing maximum grain size.

The distribution curves show that sorting is

TABLE 3.—DATA FOR CALCULATING PRINCIPAL CONSTITUENTS IN ADJUSTED WEIGHT PER CENT
(Data from Tables 3, 4, 8, 9, 13, 14)

	Coarse-grained III 9b			Medium-grained III 5b			Fine-grained III 2		
	a	b	c	a	b	c	a	b	c
Quartz	14.66	39.75	40.76	9.70	33.66	33.66	7.23	31.61	31.61
Orthoclase	3.70	6.20	4.13	2.08	2.55	4.31	2.71	4.03	3.48
Plagioclase	5.89	29.05	31.12	3.00	29.40	37.10	3.87	29.87	38.44
Biotite	0.15	1.06	1.06	0.02	1.68	1.68	0.01	1.54	1.54
Muscovite	2.97	8.20	8.20	2.57	7.76	7.76	2.37	9.17	9.17
Chlorite	1.27	9.98	10.52	0.92	16.20	9.68	1.08	17.23	9.95
Limonite	0.21	4.50	3.12	0.11	7.46	3.20	0.09	5.42	3.21
Pyrite	0.11	0.11	0.13	0.07	0.07	0.15	0.03	0.03	0.17
Apatite	0.12	0.12	0.12	0.06	0.06	0.14	0.08	0.08	0.11
Clay minerals	0.73	0.73	0.73	0.41	0.41	1.14	0.22	0.22	1.47
Carbonate	0.30	0.30	0.11	0.15	0.15	0.17	0.08	0.08	0.13
	30.11	100.00	100.00	19.09	99.40	98.99	17.77	99.28	99.28

(a) Rock fragments converted to mineral weight per cent.
(b) Total minerals in weight per cent according to results of microscopic count of grains.
(c) Total minerals in adjusted weight per cent corrected according to quantitative chemical analysis data.

poor, with the least sorting in the coarsest-grained sample. In a precise sense the term *matrix* applied to these rocks may be a misnomer in that it implies a bimodal population. The general appearance of a thin section gives an erroneous impression of the amount of matrix present, for one sees statistically distributed coarse and finer-grained quartz, feldspar, and rock fragments in a matrix of chlorite, mica, limonite, and some very fine-grained quartz and feldspar. There is no distinctly contrasting finer grain size, however. Instead, a change in mineral composition that begins at about 0.063 mm gives the impression of matrix because of the form and darker color of most of these smaller mineral grains.

In reporting the proportions of size fractions in each sample (in weight per cent) Helmbold used grade limits (Fig. 4, A) commonly assigned to the "sandy fraction" in calculations of *matrix* in graywackes, rather than clay, silt, and sand grade limits.

	Clay <0.02 mm	*Sand* 0.02 to 2. mm	*Gravel* >2. mm
Coarse-grained III 9b	9.60	85.86	4.54
Medium-grained III 5b	14.80	85.20	
Fine-grained III 2	14.54	85.46	

[If the "Wentworth" grade limits are applied instead (Fig. 4, B), the proportions are approximately:

	Clay and Silt <0.063 mm	*Sand* 0.063 to 2. mm	*Gravel* >2. mm
Coarse-grained III 9b	26	69–70	4.54
Medium-grained III 5b	38	61	
Fine-grained III 2	46	53	

According to Helmbold's calculation there is about the same amount of sand in each sample, whereas calculation based on the "Wentworth" grade scale shows a decrease in sand and a corresponding increase in clay and silt from the coarse- to fine-grained samples.]

2. *Shape of the Grains*

Measurements of roundness and sphericity (axial ratio) were made of grains larger than 0.063 mm. As used in this discussion, roundness is a neutral word without the genetic implications of "abrasion". Roundness was measured by the total angle (expressed in per cent) subtended by the convex portions of the grain boundary at the center of gravity of the grain. Roundness indices are grouped in five classes:

1. absent; 2. poor (0–33%); 3. average (33-66%); 4. good (66–100%); 5. complete (100%).

The varieties of quartz do not differ in their roundness, so the results are given collectively.

TABLE 4.—ESTIMATES OF SOURCE ROCKS OF PRINCIPAL CONSTITUENTS, IN VOLUME PER CENT
(Tables 19, 20, 21)

	Igneous	Sedimentary	Metamorphic
Rock Fragments			
(c) III 9b	40	22	38
(m) III 5b	37	28	35
(f) III 2	53	10	37
Average	43	20	37
Mineral Grains			
(c) III 9b	58	11	31
(m) III 5b	67	11	22
(f) III 2	65	11	24
Average	63	11	26
Total			
(c) III 9b	52	15	33
(m) III 5b	61	14	25
(f) III 2	62	11	27
Average	58	13	29

Moreover, quartz in the three samples does not differ significantly in its roundness index. Nevertheless, there is a correlation between grain size and roundness; the two vary directly (Table 5).

There is a small variation in the roundness indices of feldspar within the three samples, but, as with quartz, it increases with increasing grain size (Table 5). Despite their good cleavage, feldspars are better rounded than quartz because of their relative softness and ease of decomposition. Nevertheless, as in the quartz fraction, poorly rounded grains dominate.

Comparing the average roundness indices for rock fragments in the coarse-grained sample with data for quartz and feldspar reveals that fragments of sandstone and volcanic rock are much rounder and fragments of plutonic rocks, quartzites, chert, and slate are only somewhat rounder (Table 5).

Sphericity is measured by the ratio of the longest grain diameter to the axis perpendicular to it. Accordingly, the larger the ratio the less spherical the grain.

The sphericity of quartz (varieties not treated separately) is not significantly different from that of feldspar (Table 5). With both minerals the sphericity decreases with decreasing grain size.

Compared with quartz and feldspar, rock fragments measured in the coarse-grained sample (Table 5) are more commonly elongate; only the plutonic rock fragments are more nearly spherical; sandstone fragments have about the same sphericity as quartz and feldspar. Except for the plutonic rock fragments, the sequence arranged according to decreasing average sphericity of the rock types is the same as that for their decreasing average roundness.

3. *Orientation*

The three samples were examined for dimensional orientation of the grains. The smaller grains (less than 0.1 mm) show no recognizable orientation, but the larger elongate grains have an orientation which is scarcely discernible in hand specimen. In sections cut *perpendicular* to the bedding (Fig. 5) all three samples show a distinct maximum long-axis orientation parallel to bedding. Only in the fine-grained sample (III 2) is there a strong preferred orientation in sections cut *parallel* to bedding. Here the grains lie in a southeasterly trend with their blunt ends generally toward the southeast, suggesting transport from that direction.

4. *Effects of Pressure*

There are few unequivocal indications of compression. Some grains of feldspar with bent twin lamellae probably were deformed by pressure from more resistant near-by quartz grains. Moreover, the more easily bent grains of phyllite, mica, and chlorite commonly show signs of crushing.

XI. GENESIS

The investigation presented here leads to some conclusions regarding the origin of the Tanner graywacke:

The poor sorting or absence of sorting and the poor rounding are features suggesting short transport. The existence of abundant feldspar points to a swift succession of erosion, transportion, and deposition, by which thorough weathering was prevented. The very different state of preservation of the feldspar and many of the rock fragments indicates differences in

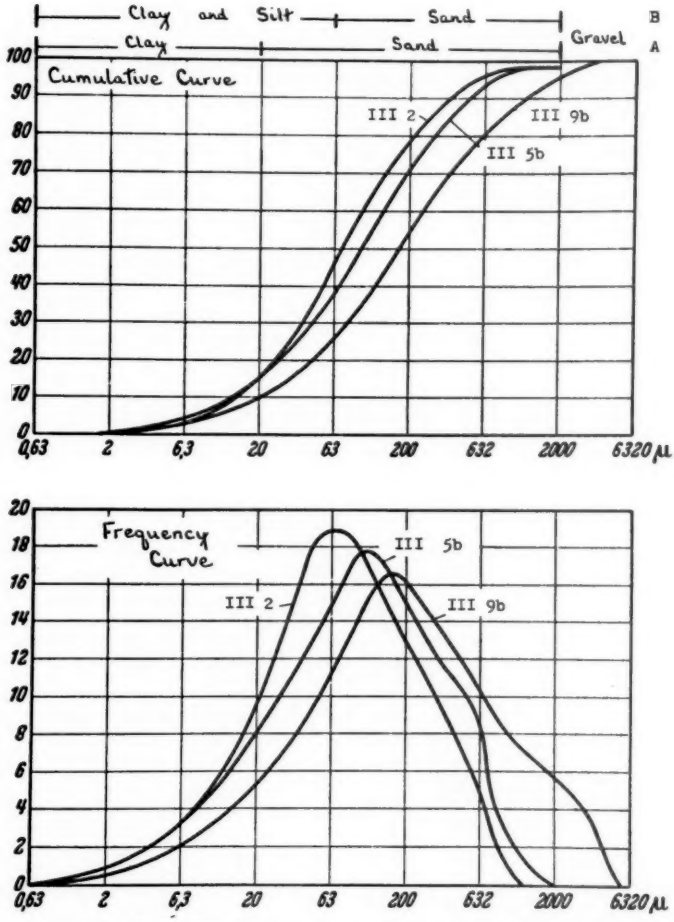

FIGURE 4.—GRAIN-SIZE DISTRIBUTIONS OF THE THREE SAMPLES STUDIED
in weight per cent
A. Grade limits used by Helmbold
B. "Wentworth" grade scale

the duration or distance of transport. The great differences in the rounding of grains of one kind of mineral also point to different distances of transport. The marked variation in grain size and thickness of bedding suggests periodic introduction of sediments by currents of varying intensity. As a cause, most authors suggest periodic uplift of the source area; possible changes in conditions of transportation due to climatic influence are generally regarded as inadequate. In fact, Krynine, Pettijohn, and others consider graywackes the typical sediments of orogenic belts.

The published interpretation of the Tanner graywacke by W. Schwan (1950) and others agrees well with this idea. During the early Variscan orogeny (Bretonic phase) at the close of late Devonian time an elongate continental ridge extending from Saar to east Halle was uplifted. Detritus eroded from this Mid-German welt was deposited in a sinking fore-deep and formed the thick sequence of the Tanner graywacke complex which today is found in a long belt that parallels the Mid-German welt and is not confined to the Harz Mountains.

The orientation of the elongate grains indicates a current from the southeast, which agrees well with this interpretation.

The characteristic contemporaneous deposition of argillaceous, sandy, and partly gravelly material in complete mixture in all graywackes is a problem that has been explained in different ways.

Table 5.—Average Class Values for Roundness and Sphericity

(Data from Tables 24, 25, 26, 27, 28, 29)

	Roundness				Sphericity	
	(f) III 2	(m) III 5b	(c) 9b III	Total range	(m) III 5b	(c) III 9b
Quartz	1.73	1.74	1.79	2.1–1.6	1.85	1.74
Feldspar	1.86	1.94	1.98	2.2–1.7	1.87	1.74
Sandstone	....	....	3.19	....	....	1.73
Volcanic rock	....	....	3.08	....	....	1.83
Plutonic rock	....	....	2.39	....	....	1.63
Quartzite	....	....	2.32	....	....	2.06
Chert	....	....	2.25	....	....	2.52
Slate	....	....	2.10	....	....	3.68

Pettijohn (1949, p. 253) agreed with Woodland (1938) in the opinion that "the fine-grained matrix, once a colloidal suspension of clayey aluminous and siliceous materials, was subject to constant flocculation, thereby becoming a constant component of all rocks of this group.... Salt water may have been the precipitating [flocculating] agent".

This explanation seems improbable, however, because a current that can still transport gravel or just deposit it carries away the finer-grained material. In this way sorting results; but the absence of sorting is a distinguishing feature of graywacke.

Krynine (1945) regards the matrix as predominantly detrital material from easily disintegrated slate, phyllite, and other schistose rocks. Nevertheless, he also points out that there has been some readjustment and reorganization.

Irving and Van Hise (cited in Pettijohn, 1949, p. 245) attributed the entire matrix to sericite-chlorite alteration of feldspar.

As Kuenen [and Migliorini] (1950) have shown, low-velocity suspension currents which, in contrast to mudflows, always flow turbulently are able to transport even coarse grains owing to their great density. When they come to a halt they produce deposits with graded bedding which, as graywacke, contain a mixture of all grain sizes. Kuenen and Migliorini [1950] regard most deposits with graded bedding as products of that kind of suspension [turbidity] current.

Kuenen's published description of the formation of such deposits simultaneously provides the best explanation for several phenomena of graywackes that are difficult to account for: the presence of completely mixed fine- and coarse-grained detritus, the graded bedding of individual layers, the marked variation in thickness of different strata, and the interbedded shale and argillite. The shale and argillite represent the normal deposit of the particular marine realm, into which suspension [turbidity] currents of varying intensity spread periodically; these carry with them coarse sediment of the near-shore realm and deposit it in deeper water along with the argillaceous material.

This interpretation agrees with Krynine's view that detrital debris predominantes even in the finest fraction. Part of this material may come from sericitization of feldspar that already occurred prior to transport, for the sericitized feldspar would disintegrate fairly easily. After deposition, continued transformation and reconstruction will take place, so that there results a thickly woven mixture of chlorite, sericite, and in same cases clay minerals as well, which is permeated with limonite, quartz, and feldspar. This fine-grained heterogeneous mixture is generally called "matrix".

XII. Comparison with Newer Definitions of Graywacke

Pettijohn and Krynine subdivide detrital sediments similarly on the basis of the relative proportions of quartz, feldspar, and mica plus chlorite. According to Pettijohn [1949, Fig. 66; p. 244–249], the essential difference between graywacke and other types (quartzose sandstone and arkose) is the [detrial matrix composed principally of] chlorite and mica that characterizes graywacke. The lower limit is set at 20 per cent. Graywacke with less than 10 per cent feldspar is called "subgraywacke".

In a similar way Krynine [1948, Fig. 4] draws the lower limit of the mica-chlorite content of graywackes at 17 per cent. He differentiates between "low-rank" graywacke with less than

17 per cent [10%; 1948, Table 3] feldspar, which is similar to Pettijohn's "subgraywacke", and "high-rank" graywacke with a feldspar content between 17 [10] and 40 per cent. Detrital sediments with more than 17 per cent graywacke as "a clastic rock containing a substantial amount (20 per cent or more) of dark rock fragments or dark-colored ferromagnesian minerals". This presence of rock fragments, which Pettijohn also described, is not

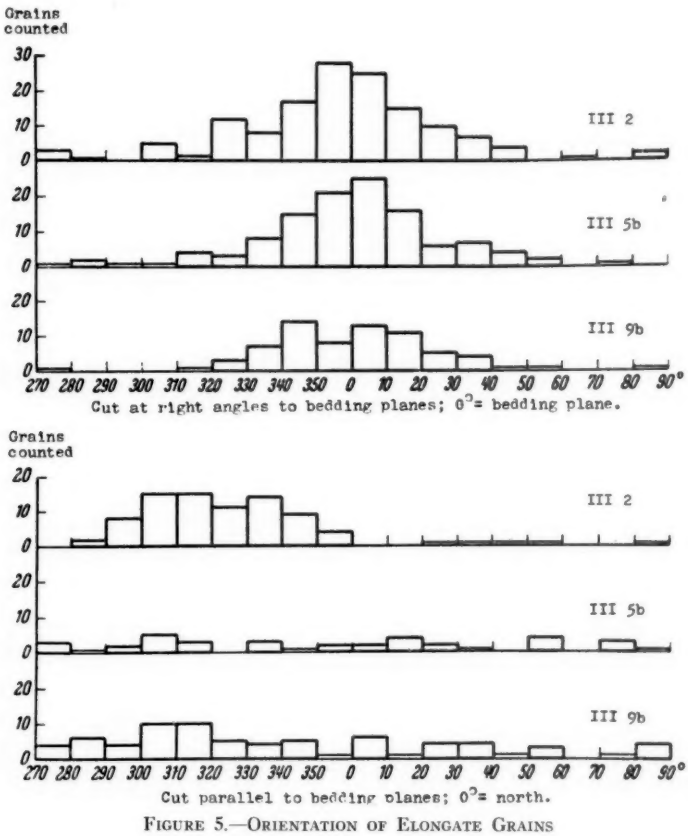
Grains counted
30
20
10
0
III 2
III 5b
III 9b
270 280 290 300 310 320 330 340 350 0 10 20 30 40 50 60 70 80 90°
Cut at right angles to bedding planes; 0° = bedding plane.
Grains counted
20
10
0
III 2
III 5b
III 9b
270 280 290 300 310 320 330 340 350 0 10 20 30 40 50 60 70 80 90°
Cut parallel to bedding planes; 0° = north.

FIGURE 5.—ORIENTATION OF ELONGATE GRAINS

mica-chlorite component and more than 40 per cent feldspar are called "impure arkose".

According to the limits set by both authors the [medium- and fine-grained] Tanner graywacke, which contains less than 15 per cent mica-chlorite and more than 40 per cent feldspar in weight per cent, would be called an arkose. [Helmbold has overlooked the fact that both Pettijohn and Krynine point out that the principal feldspar in arkose is orthoclase, not plagioclase, a distinction obscured in their diagrams, however.]

In another place, Krynine (1940) defined included in the fore-mentioned definitions, but in Germany it is considered the characteristic feature of graywackes, according to Salomon (1915), Correns (1939; 1949), and others.

With all authors who have proposed definitions, the most distinctive character of graywacke is the poor sorting or lack of it and the poor rounding of the grains; this feature fits the Tanner graywacke.

The qualitative specifications of the chief components of graywacke agree on the whole with the composition of the Tanner graywacke. In addition, the paucity of Fe-Mg minerals

other than chlorite and mica noted in most discussions of graywacke also characterizes the Tanner graywacke.

Although the Tanner graywacke contains less mica-chlorite than "high-rank" graywackes,

TABLE 6.—COMPARISON OF PRINCIPAL CONSTITUENTS OF GRAYWACKES

(Data from Tables 2, 3, 7, 8, 12, 13, 18)

	A	B	C	D	E
Quartz	24.6	45.6	24.6	46.0	35.2
Feldspar	32.1	16.7	32.1	20.0	39.2
Rock fragments	21.7	6.7	21.7	....	....
Chert	1.3	1.1	1.3	7.	1.3
Mica-chlorite	13.9	25.0	20.0	22.5	18.7

A. Tanner graywacke (average of 3 analyzed specimens); microscopic count in volume per cent (Table 2, a) used here because this is the method of analysis employed by Pettijohn and Krynine.

B. Pettijohn (1949, Table 63, A; 1957, Table 50, A). Average of 6 graywackes.

C. Tanner graywacke (average). Inasmuch as most of the limonitic material occurs in the matrix it is calculated with the mica-chlorite in accordance with Pettijohn's view that the mica and chlorite are authigenic matrix minerals (Pettijohn, 1957, Table 50, C; p. 305).

D. Krynine (1948, Fig. 11). Percentages refer to total composition, including minerals in rock fragments and matrix.

E. Tanner graywacke (average). Percentages refer to total composition, including minerals in matrix and those in rock fragments in accordance with Krynine's view that most of the minerals in the matrix, like the rock fragments, are of detrital origin (Krynine, 1948, p. 152).

its probable mode of origin and high feldspar content agree well with Krynine's comment 1948, p. 152–153): "High-rank or feldspathic graywackes are formed in narrow and rapidly subsiding geosynclines .... Feldspar ... may be abundant in the high-rank feldspars. In this case it is usually a sodic plagioclase".

In the details of its quantitative composition the Tanner graywacke deviates substantially from the values published by Pettijohn and Krynine (Table 6).

XIII. SUMMARY

With the aim of making as accurate as possible a qualitative and quantitative description of the Tanner graywacke from the Scharzfeld quarries, three samples of different grain size were examined and the results compared with one another and with other graywackes.

The samples were quantitatively chemically analyzed. The mineral and rock components were determined and described. The quantitative amount of the components was determined in thin section by a Rosiwal analysis modified to accommodate the peculiarities of the rock. The results were converted into chemical values and compared with the chemical-analysis results. Furthermore, estimates of the rock types in the source area were made. The important fabric characteristics were ascertained for a critical appraisal of the genesis of the rock: the grain-size distribution of the entire rock and of the chief components, the grain shape with estimates of roundness and sphericity (axial ratio), the orientation of the elongate grains, and finally the effects of pressure. The current ideas concerning the probable manner of origin were discussed on the basis of the results of this investigation, and the total picture of the Tanner graywacke resulting from the individual analyses has been compared with recently proposed definitions of graywacke.

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STRATIGRAPHY OF THE COW HEAD REGION, WESTERN NEWFOUNDLAND

BY C. H. KINDLE AND H. B. WHITTINGTON

ABSTRACT

Seashore exposures in the Cow Head area display a succession of limestone conglomerates interbedded with shales and limestones. Conglomerate layers range in thickness from 1 foot to more than 200 feet. The material consists of flat angular chips or moderately rounded boulders of fine-grained gray or white limestone. Fossiliferous boulders from any one layer yield trilobites of the same limited age.

Boulders from the lowest fossiliferous conglomerate at Broom Point contain *Kootenia*, *Zacanthoides*, *Orriella*, *Agraulos*, and *Peronopsis*. Succeeding bedded limestone yields *Meneviella* and *Tomagnostus*. A boulder in the overlying conglomerate also contained *Meneviella* and *Tomagnostus*.

Cambrian conglomerates at Cow Head yield younger trilobites in successive layers: *Tricrepicephalus* appears in the lower, then *Taenicephalus*, followed by *Ctenopyge*, *Rasettia*, and *Keithiella*. Above are beds with *Staurograptus* and *Dictyonema*, overlain by conglomerates with early Ordovician trilobites.

Successively higher black shales contain graptolites of the Levis Shale zones, and interbedded conglomerates yield successively younger Ordovician trilobites. Shale with *Trigonograptus* and *Isograptus* underlies the highest conglomerate which yields *Nileus*, *Bathyurellus*, *Remopleurides*, and *Ectenonotus*. The thick limestone conglomerate at Lower Head includes enormous boulders, one of which contains many of the trilobites described by Billings (1861–1865) as from Cow Head. This layer is underlain by black shale with *Isograptus*.

The Cow Head Group, therefore, is not a single formation but a succession of conglomerates and intervening beds ranging in age from Middle Cambrian to Middle Ordovician. With few exceptions the boulders of any conglomerate are approximately the same age as the immediately underlying strata. The limestones of the fossiliferous boulders formed in shallow water; the beds intervening between the conglomerate layers formed in deeper water and consequently are almost devoid of fossils other than graptolites.

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Introduction and Acknowledgments

Schuchert and Dunbar (1934) provided the foundation on which geologic mapping in western Newfoundland was conducted by the Geological Survey of Newfoundland for the next 12 years. In 1938, 1939, and 1945 Kindle was invited to assist Dr. Helgi Johnson in this work. Limestone conglomerates encountered were regarded, in part, as puzzling thrust breccias.

In 1952 Kindle again visited the Cow Head area to assemble dip and strike data for the John Fox oil drilling interests. These data indicated an orderly arrangement in the supposedly chaotic Cow Head "breccia." In the same year Philip Oxley of the Geological Survey of Newfoundland discovered a layer of Middle Cambrian agnostids at Broom Point in a block which had fallen from strata between layers of limestone conglomerate. This led to the realization that some of the Cow Head conglomerates must be Middle Cambrian. Oxley also found *Endymionia*, a Table Head trilobite, in thin-bedded limestones below limestone conglomerates at the Inner Tickle of St. Paul's Inlet. Thus some of the limestone conglomerates must be Middle Cambrian, others Middle Ordovician. A reinvestigation of the stratigraphy of the conglomerates and associated strata in the Cow Head area is necessary to provide a secure foundation for proposed faunal studies.

Accordingly the writers spent 7 weeks in 1955 in western Newfoundland. On Cow Head peninsula and at near-by exposures abundant evidence was found that the Cow Head limestone conglomerates range from Middle Cambrian to Middle Ordovician. The structure and stratigraphy of Cow Head peninsula are so at variance with published views that a preliminary report is advisable. The identifications of fossils herein are preliminary, and the faunas will be described in detail in a later publication.

Detailed topographical maps of the region are not available, but the Hydrographic Office charts are useful for the coastal regions. Aerial photographs, scale 2 inches to 1 mile, are obtainable from the National Air Photo Library in Ottawa, Canada.

The writers are indebted to the Council of The Geological Society of America for grant 671-55 of the Penrose Bequest which enabled them to undertake the field work. Whittington received a grant from the Harvard Foundation for Advanced Study and Research which made it possible for him to study type specimens of trilobites described by Billings (1861–1865), through the kind permission of Dr. H. Frebold at the Geological Survey of Canada, Ottawa.

The hospitality and assistance of many friends in western Newfoundland, and Mrs. Whittington's contributions to the fossil collection are gratefully acknowledged.

General Statement on Stratigraphy

Schuchert and Dunbar (1934) described the outcrops on Cow Head peninsula and adjacent areas in detail, and "were forced to interpret these lenticular masses of coarse breccia as the materials of talus and landslides formed along a fault scarp that came into existence during Mid-Ordovician orogeny" (p. 84). They also recognized that a sequence of shales, siltstones, and limestones cropped out at Martin Point, Broom Point, and St. Paul's Inlet but considered that this sequence belonged to the Green Point Series of earliest Ordovician age and was older than the St. George Series (Table 1; Schuchert and Dunbar, 1934, p. 39).

Johnson (1941) was the first to show that these rocks were, in the Cow Head region, Lower and Middle Ordovician and thus a different facies from the St. George and Table Head Series. He proposed two new stratigraphical names (Table 1) and commented that there were several horizons of intraformational conglomerates as well as the Cow Head breccia (1941, p. 143).

Oxley (1953) published the first detailed map of the region between Portland Creek Pond and Martin Point, using a combination and emendation of earlier stratigraphical divisions (Table 1). He recognized two facies in the Lower Ordovician—the Green Point-St. Paul Group and the St. George-Table Head Group—and regarded the Cow Head Breccia as overlying both.

The 1954 map of the Newfoundland Department of Mines and Resources, Mines Branch, Geological Survey shows undifferentiated

Ordovician rock in this area; the 1955 map of the Department of Mines and Technical Surveys, Geological Survey of Canada leaves the area blank. Fossils from the Cow Head region have been listed by Schuchert and Dunbar (1934), Kindle (1943), Ruedemann (1947), and Oxley (1953). Descriptions of Cambrian and Early Ordovician trilobites have been published by Billings (1861–1865), Raymond (1925), Lochman (1938), Kindle (1942; 1948), and Rasetti (1954).

TABLE 1.—STRATIGRAPHICAL CLASSIFICATION IN THE COW HEAD REGION

	Schuchert and Dunbar (1934) Lochman (1938)	Johnson (1941)		Oxley (1953)		This paper
Middle Ordovician	Humber Arm Series Cow Head Breccia Long Point Series Table Head Series	Humber Arm Group		Humber Arm Group Cow Head Breccia		Unnamed green sandstones
		Portland Head Group	St. Paul's Group			
Lower Ordovician	St. George Series	Table Head Group	Western Brook Pond Group	Table Head St. George Group	St. Paul Green Point Group	Cow Head Group
	Green Point Series	St. George Group	Green Point Group			
Middle and Upper Cambrian	Petit Jardin Formation	?				
	March Point Formation	?				

The writers believe that on Cow Head peninsula and certain adjacent coastal regions (Fig. 1) a sedimentary series ranging from Middle Cambrian to Middle Ordovician is exposed. This group of strata is about 1000 feet thick, consisting of thin-bedded limestones with shale partings and interbedded shales, and, rarely, sandstones; at intervals throughout the sequence occur spectacular beds of limestone conglomerates. Some of the boulders and blocks in these conglomerates are fossiliferous, and in any one layer are all about the same age The beds on which a particular conglomerate layer rests are about the same age as the blocks in the overlying conglomerate. This is true throughout the sequence, and thus these conglomerate layers are intraformational and were brought into place periodically during Middle Cambrian to Middle Ordovician time. Oxley (1953, p. 11) was the first to list Middle Cambrian trilobites from this region. These are said to come from a boulder in a conglomerate but actually came from a block of the bedded limestone which had fallen to the shore. The writers found Middle Cambrian trilobites in bedded limestones and also in conglomerate boulders. Upper Cambrian trilobites have been found only in boulders in younger conglomerate layers. In the Ordovician part of the sequence the writers established a zonal sequence of graptolites from finds of these fossils in the bedded shales and dark limestones. The successively younger interbedded conglomerates have yielded an orderly succession of trilobite faunas. The late Middle Cambrian to Middle Ordovician part of the sequence is exposed along the shores of Cow Head peninsula. Older Middle Cambrian conglomerates crop out on the neighboring White Rock Islets but are best displayed at Broom Point, 6 miles to the south–southwest. Pending further studies which may give a more detailed picture of the stratigraphy, it seems simplest to use the name Cow Head Group (an emendation of Schuchert and Dunbar's Cow Head Limestone Breccia) for this Middle Cambrian to Middle Ordovician sequence, rather than to introduce new names.

The Cow Head Group, like the Table Head Series, is overlain by a clastic sequence with characteristic greenish sandstones. The writers have not studied these rocks in detail and have not used either an old or a new name in referring to them (Table 1).

The limestone conglomerates of the Cow Head Group, both physically and in their faunas, are remarkably like those of Levis and other localities along the south shore of the St. Lawrence River. Both the Cambrian and Ordovician trilobites in these conglomerates show affinities with those of near-by areas as well as with Utah and Nevada and with Europe. This mixture of Atlantic and Pacific faunas affords new correlation possibilities. The Ordovician graptolite zones are like those of southern Australia, rather than those of western Europe. This unique alternation of graptolite and trilobite faunas enables the writers to make a tentative correlation between zones established on these two groups. Two and perhaps three facies can be recognized during Cow Head Group time in western Newfoundland, but the spatial relationship of these facies cannot yet be clearly portrayed. The earliest folding and thrusting for which there is clear evidence in the Cow Head region is post-Cow Head Group, *i.e.*, later than early Middle Ordovician. Earlier tectonic activity must have produced the blocks in the conglomerates and the submarine slopes down which they moved into place in the Cow Head Group. Since rocks older than Middle Cambrian were not encountered in the shore exposures Table 1 does not include the Lower Cambrian formations that occur a few miles inland.

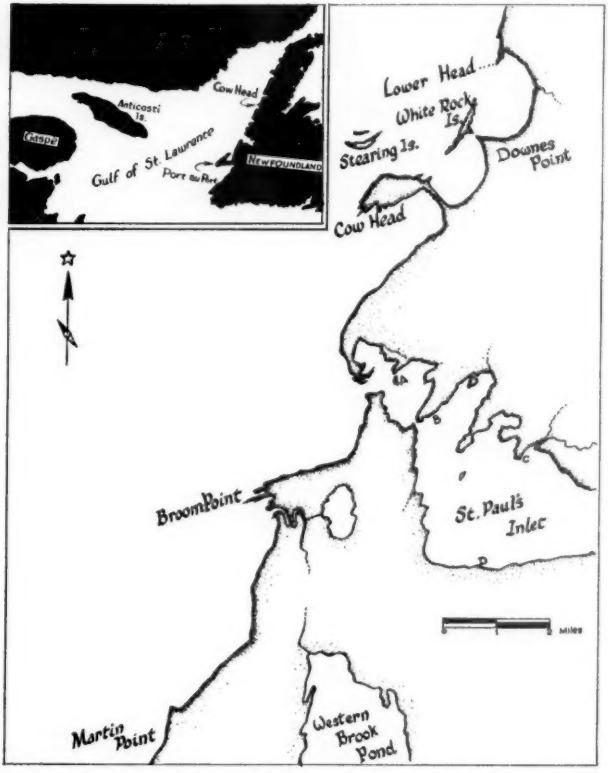

FIGURE 1.—MAP SHOWING LOCATION OF COW HEAD REGION

In St. Paul's Inlet A shows location of Green Island (Late Cambrian); B and C show locations of Figures 5B and 5A; and D shows location of White Point (Middle Cambrian).

TABLE 2.—CORRELATION OF CAMBRIAN FAUNAS OF THE COW HEAD REGION

	Equivalent American faunal zones	Cambrian faunas of the Cow Head area	Occurrence	Equivalent Swedish faunal zones
Upper Cambrian	*Hungaia magnifica* fauna (Trempealeauian)	*Theodenisia* *Rasettia* *Plethometopus* *Keithiella* *Loganopeltoides* *Ctenopyge*	Bed 6 Cow Head	Zone 5 of the Olenid Series (with *Ctenopyge*)
	Taenicephalus sub-zone (Franconian)	*Taenicephalus* *Parabolinella*	Bed 5 Cow Head	? Zone 4 of the Olenid Series
Middle Cambrian	*Paradoxides forchhammeri* zone (Dresbachian)	*Coosella* *Catillicephala* *Deirocephalus* *Hemirhodon* *Kingstonia* *Meteoraspis* *Tricrepicephalus*	Beds 1, 3, 4 Cow Head	STAGE OF *PARADOXIDES FORCHHAMMERI* Zone C3—*Lejopyge laevigata* Zone C2—*Solenopleura brachymetopa* Zone C1—*Ptychagnostus lundgreni*
	Paradoxides davidis zone *Paradoxides hicksi* zone	*Hypagnostus* *Peronopsis* *Meneviella* *Tomagnostus fissus*	Broom Point	STAGE OF *PARADOXIDES PARADOXISSIMUS* Zone B4—*Ptychagnostus punctuosus* Zone B3—*Hypagnostus parvifrons* Zone B2—*Tomagnostus fissus* Zone B1—*Ptychagnostus gibbus*
	----------?	*Agraulos* *Orriella* *Kootenia* *Zacanthoides* *Peronopsis* *Ptychagnostus* cf *gibbus*	Broom Point and White Rock Islets	----------?

DETAILS OF STRATIGRAPHY

Cow Head Peninsula

The writers' observations on Cow Head peninsula are summarized in the map (Fig. 2), the columns (Fig. 3), and in Table 2. The writers believe that the peninsula shows a conformable series of interbedded limestones, shales, and conglomerates, about 800 feet thick. From bedded limestones of bed 3, cropping out on the northeast shore, come fossils of Dresbach age (equivalent to the *Paradoxides forchhammeri* zone) and from black shales of bed 13, on the southwest shore, come graptolites of early Middle Ordovician age. The rocks of the peninsula are folded into a syncline and an anticline, the axes of which trend about N. 15° E. and are cut by normal faults of small displacement. The northeastward-trending normal fault at the northeast tip of the peninsula is shown in Schuchert and Dunbar (1934, Pl. 10B). Another such fault on the southeast shore (not indicated on Figure 2), which cuts beds 8d (limestone and shale) and 8e (conglomerate), is figured by Schuchert and Dunbar (1934, Plate 9B) and shows a relative downward displacement of the conglomerate on the west (right side of the figure).

The oldest stratum on the peninsula seems to be the conglomerate layer 1 which forms the outer edge of the point northwest of Tucker's Cove and is also exposed at low tide in Beachy

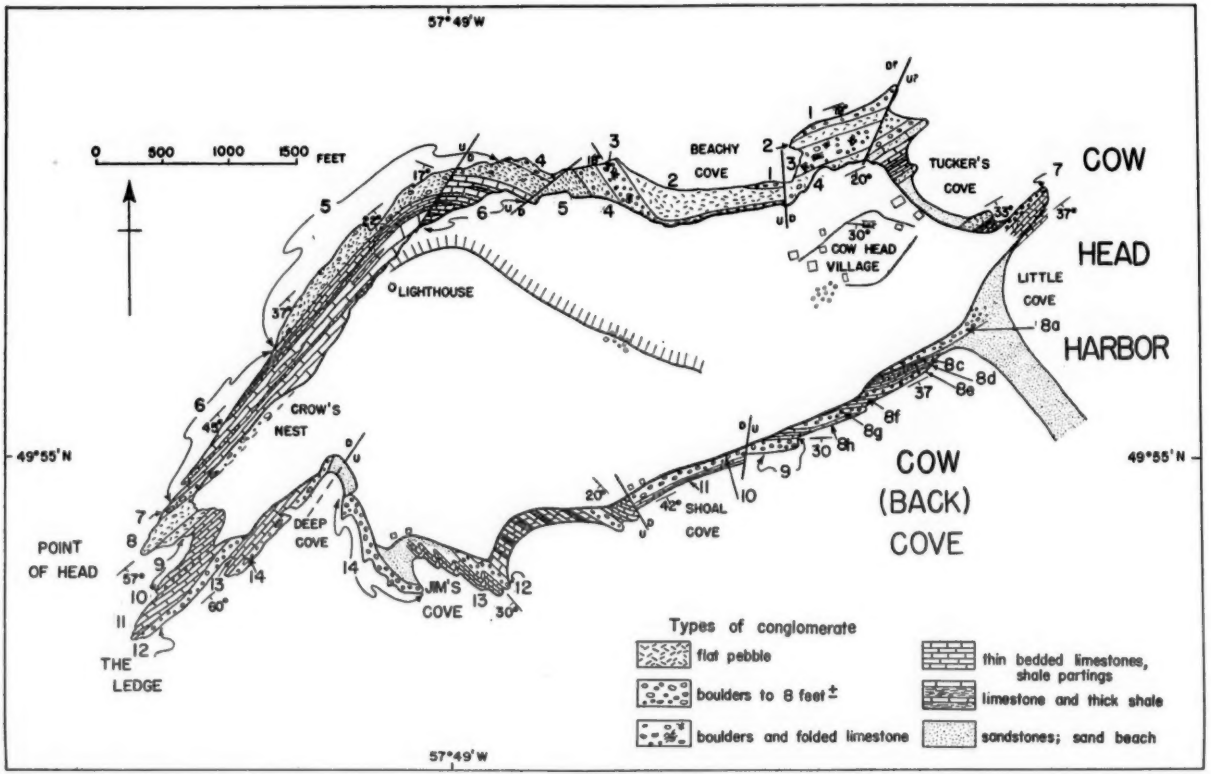

FIGURE 2.—GEOLOGICAL MAP OF COW HEAD PENINSULA

FIGURE 2.—GEOLOGICAL MAP OF COW HEAD PENINSULA

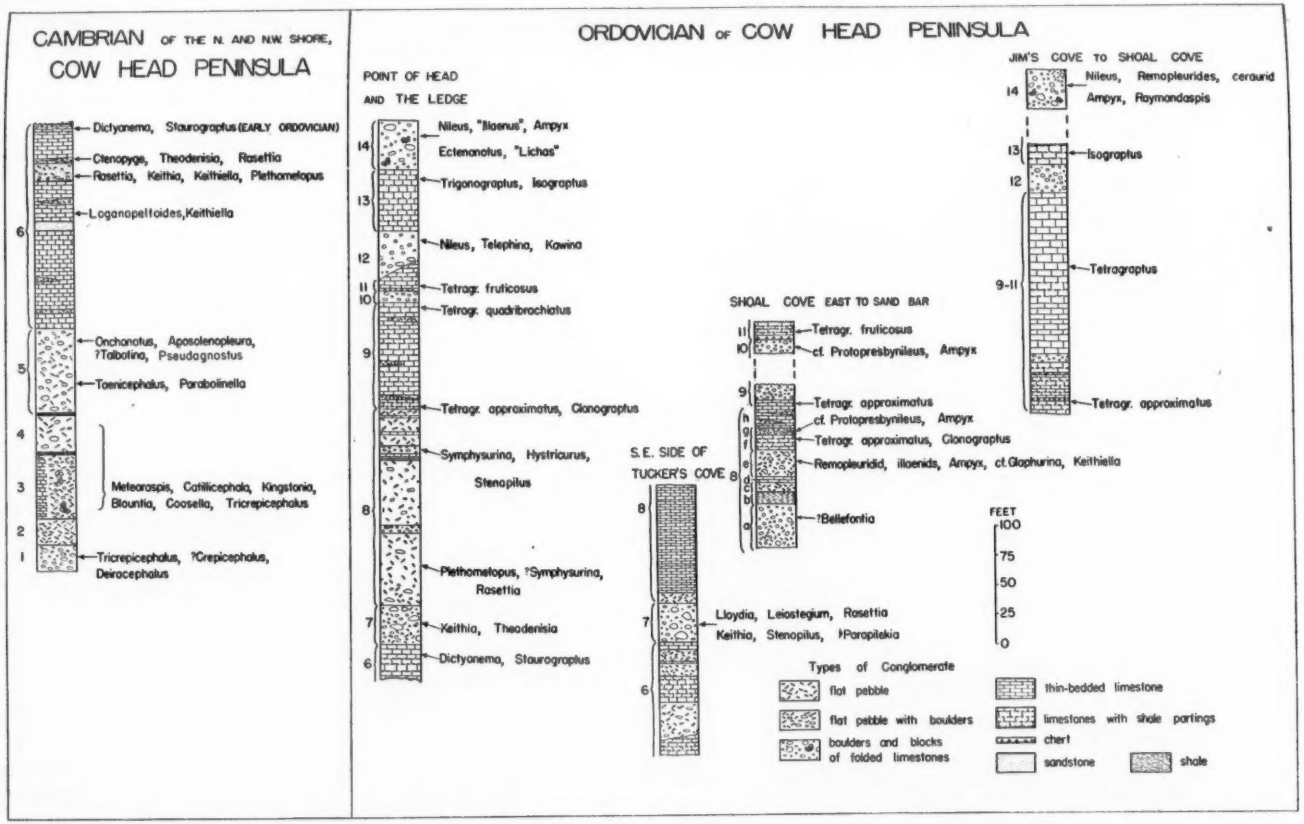

FIGURE 3.—COW HEAD STRATIGRAPHIC COLUMNS

Cove. This layer is at least 6 feet thick and contains many limestone boulders up to 3 feet in size. From some of these boulders the writers obtained *Tricrepicephalus* sp., *Crepicephalus* sp., and *Deiracephalus* sp. Bed 1 is cut off on the east by a northeastward-trending fault. East of this fault, at the northwestern end of Tucker's Cove, the following descending section, dipping about 20° to the south is exposed on the shore and in the cliffs:

Feet	
c. 15	Limestones and shales and interbedded 2-foot layers of flat pebble conglomerate. Rounded quartz grains occur in the matrix of some of these conglomerates.
c. 90	Shales and limestones with some conglomerate lenses. These strata are shown in Schuchert and Dunbar (1934, Pls. 10A and 10B, left side).
c. 28	Calcareous sandstone with some conglomerate.
c. 15	Coarse limestone conglomerate, boulders up to 3 feet in maximum dimension.
c. 3	Shale.
	Up to 30 feet of limestone conglomerate exposed east of the fault, boulders up to 3 feet.

Higher beds in this section are concealed by the sandy beach of Tucker's Cove, but if this section is continuous with that on the southeast side of the cove, then, judging by thicknesses, the lower beds must be about the same age as bed 1 but might be slightly older. No fossils were found in the bedded strata, and the conglomerates were not searched intensively.

Beds 2 and 3 are well exposed in Beachy Cove. The former is a flat pebble conglomerate from which no fossils were obtained. Bed 3 may be seen along the foot of the cliff at Beachy Cove; in places it consists entirely of thin-bedded limestones, and in other places these limestones pass laterally into limestone conglomerate (Pl. 1, fig. 1). The conglomerate includes large blocks of thin-bedded, greenish limestones with the bedding in the blocks usually bent or thrown into folds. The conglomerate is shown in Schuchert and Dunbar (1934, Pl. 9A). The writers found fossils similar to those obtained by Schuchert and Dunbar (Lochman, 1938, p. 463–464) in the bedded portions and conglomerate blocks of bed 3. These include *Meteoraspis* sp., *Catillicephala* sp., *Kingstonia* sp., *Blountia* sp., *Tricrepicephalus* sp., and *Coosella* sp. Lochman (1938) considered them to belong to the *Crepicephalus* zone of the Dresbach. The latter stage is now regarded as late Middle Cambrian (Lochman, 1956, p. 447).

Bed 4 is visible on the shore west of Beachy Cove, near a path that descends the cliff. It is a conglomerate with boulders up to 5 feet in diameter. Several smaller boulders proved abundantly fossiliferous, and from them the writers identified: *Catillicephala* sp., *Coosella* sp., *Kingstonia* sp., *Ithycephalus* sp., *Tricrepicephalus* sp., *Meteoraspis* sp., *Bienella* sp., *Millardia* sp., and *Deirocephalus* sp. These boulders are apparently of about the same age as those of bed 3.

Bed 5, separated from bed 4 by a 1-foot band of shale and limestone, includes 60–70 feet of limestone conglomerates predominantly of small, flat chips, with scattered larger boulders up to about 3 feet in length. This bed forms a rampart for more than a quarter of a mile along the northwest shore. Several of the larger boulders were highly fossiliferous. The following occurred in a boulder 30 feet from the sea in front of the lighthouse: *Taenicephalus* sp., *Parabolinella* sp., and *Pseudagnostus* cf. *gyps*. From a boulder much farther west and nearer the top of the bed the writers collected *Onchonotus* sp., ? *Aposolenopleura* sp., *Talbotina* ? *levisensis*, *Loganopeltoides* sp., and *Pseudagnostus* cf. *gyps*. *Taenicephalus* is charac-

PLATE 1.—COW HEAD GROUP ON COW HEAD

FIGURE 1.—Bed 3, cliff at Beachy Cove, Cow Head peninsula, showing bedded limestones passing laterally into conglomerate.

FIGURE 2.—Looking south across The Ledge, southwest tip of Cow Head peninsula. Arrows point to base of conglomerate bed 12, which cuts downward across bed 11.

PLATE 2.—COW HEAD GROUP ON COW HEAD

FIGURE 1.—Cliff at Crow's Nest, looking southeast from the sea off Cow Head peninsula. Bed 7 (with large boulders) runs diagonally up the cliff, which is about 100 feet high. Sea is breaking against bed 5, behind which the lower part of bed 6 is concealed.

FIGURE 2.—Shore west of lighthouse, Cow Head peninsula, looking northeast. Sandstone rib in bed 6 is to right of center; base of bed 7 is in cliff.

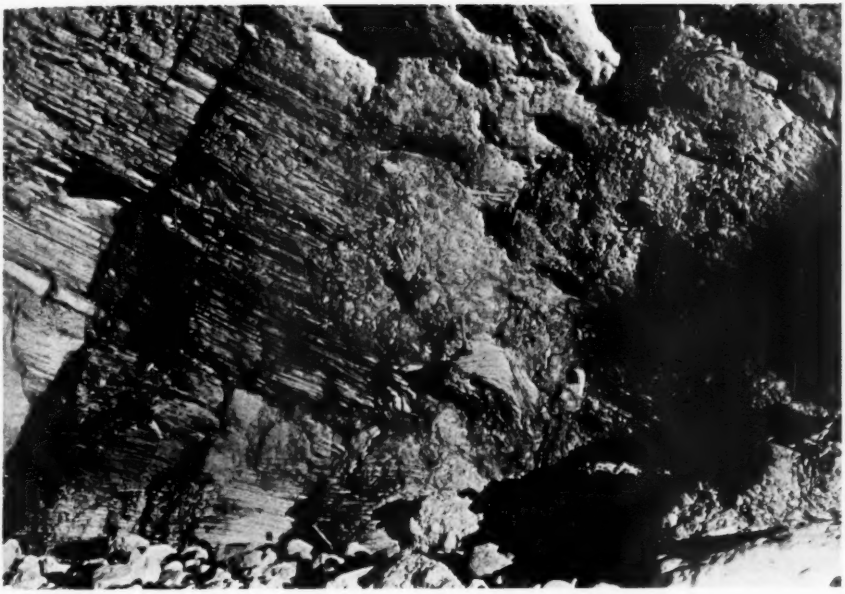

FIGURE 1

FIGURE 2

COW HEAD GROUP ON COW HEAD

FIGURE 1

FIGURE 2

COW HEAD GROUP ON COW HEAD

FIGURE 1

FIGURE 2

COW HEAD GROUP ON COW HEAD AND EXPOSURES AT GREEN POINT

FIGURE 1

FIGURE 2

BOULDER IN BED 6, COW HEAD, AND CONGLOMERATE AT LOWER HEAD

teristic of the *Conaspis* zone of the Franconian Stage of the Upper Cambrian.

Bed 6 forms the lower ground between the wall made by bed 5 and the base of the cliff and extends up the lower part of the cliff (Pl. 2, fig. 2). The greater part of the bed is thin-bedded limestones and shales, but there are lenses of conglomerate of small flat limestone chips and a few boulders. An 8-foot layer of limy sandstone with rounded quartz grains occurs near the middle of bed 6 and forms a conspicuous rib running along the shore. Similar sand grains in the matrix of the conglomerates and forming calcareous sandstones occur throughout the upper half of bed 6; sandstones associated with the higher conglomerate form a second conspicuous rib (Pl. 3, fig. 1). These sandstones were noted by Schuchert and Dunbar (1934, p. 76). The position of the ribs is indicated on the map (Fig. 2). Figure 1 of Plate 4 shows an isolated boulder of light limestone resting in thin limestone and shale of the upper part of bed 6 near the base of the cliff. Smaller boulders similarly situated were observed near by. Fossils in the few larger boulders in conglomerates in the upper part of bed 6 (Pl. 2, fig. 2) were of one fauna: *Ctenopyge* cf. *flagellifera*, *Theodenisia* sp., *Rasettia* sp., *Keithia* sp., *Keithiella* sp., *Plethometopus* sp., ? *Loganopeltoides* sp., and ? *Loganellus* sp. All these trilobites except *Ctenopyge* are present in Upper Cambrian faunas from the boulders of the Levis Formation (Rasetti, 1944, 1945), and similarity in age is indicated. From thin-bedded limestones with shale partings 3–5 feet below the top of bed 6 the graptolites *Staurograptus* sp. and *Dictyonema* sp. were collected; these are characteristically Early Ordovician (*i.e.*, Tremadoc or lowest Lancefield Series of Victoria). No fossils were found in the limestone and conglomerates of bed 6 which crop out on the southeast side of Tucker's Cove.

Succeeding bed 6 is a prominent band (bed 7), 30–50 feet thick, of conglomerate with many large boulders up to 6 feet in length. Some of the large boulders are brown limestone, but many are white limestone. Consequently bed 7 is conspicuous where it runs along the top of the cliff at Crow's Nest (Pl. 2, fig. 1) and out to Point of Head. As seen in this cliff the conglomerate rests on a slightly uneven base on the thin-bedded limestones, and in places these limestones are disturbed or broken, which suggests that they were torn up as the conglomerate was deposited. Southwest of the lighthouse the outcrop of bed 7 swings inland and is seen in the prominent cliffs that run east-southeast across the peninsula south of the lower ground behind the village. Apparently the same band reappears on the southeast side of Tucker's Cove and again forms a conspicuous rib of large white and brown boulders. Fossils were obtained from white limestone boulders at three places:

Near Point of Head:

Keithia sp.
Theodenisia sp.
Rasettia sp.
cf. *Bayfieldia* sp.
Stenopilus sp.
Leiocoryphe sp.
Plethometopus sp.
? *Phoreotropis* sp.
? aff. *Loganellus* sp.

From one boulder at the top of the cliff near the center of the peninsula, about half a mile west of the village:

Parabolinella sp.
Symphysurina sp.
Rasettia sp.
Pseudohystricurus sp.
Bienvillia sp.

PLATE 3.—COW HEAD GROUP ON COW HEAD AND EXPOSURES AT GREEN POINT

FIGURE 1.—North side of Point of Head, looking southwest, Cow Head peninsula. Upper part of bed 6 with sandstone rib; bed 7 forms cliff.

FIGURE 2.—Section at Green Point. Arrow indicates fossiliferous Green Point Formation.

PLATE 4.—BOULDER IN BED 6, COW HEAD, AND CONGLOMERATE AT LOWER HEAD

FIGURE 1.—Isolated limestone boulder in thin-bedded limestone of upper part of bed 6, foot of cliff below lighthouse, Cow Head peninsula.

FIGURE 2.—West side of tip of Lower Head, looking south. In left foreground is part of large block of white limestone with surrounding conglomerate to right; arrows point to edge of large block. In right background is Cow Head peninsula.

From the southeast side of Tucker's Cove:

Lloydia sp.
Leiostegium sp.
Rasettia sp.
Keithia sp.
Stenopilus sp.
? *Onchonotus* sp.
? *Hystricurus* sp.
cheirurid of *Parapilekia* type

The fauna from Point of Head is of the *Hungaia magnifica* zone of boulders in the Levis conglomerate (Rasetti, 1944, 1945), regarded by Rasetti as late Upper Cambrian (Trempealeau) age but by Shaw (1955) as "probably Franconian." Faunas from the other boulders show a mingling of some of these Levis fossils with genera commonly regarded as Early Ordovician, including *Symphysurina*, *Pseudohystricurus*, *Lloydia*, and *Leiostegium*. The strata immediately below bed 7 are Early Ordovician and thus at least some of the boulders in the conglomerate were formed penecontemporaneously with the beds on which it rests. Even if the boulders with the *Hungaia* fauna are regarded as older and of Upper Cambrian age, at least some of the elements in this fauna may range into the Lower Ordovician. The Tremadoc fauna described by Shaw (1951; 1955) from northwestern Vermont includes *Parabolinella* and *Symphysurina*, but the other species do not resemble those from Newfoundland.

Point of Head is formed not only by bed 7 but by 150 feet of overlying conglomerate, here called bed 8. Most of this bed is composed of small flat chips of limestone in a fine-grained matrix, but lenses of coarser conglomerates occur, and in the upper part are layers of a few feet of thin-bedded limestone. Blocks of limestone 2 to 4 feet in length occur rarely, but at most levels, in the chip conglomerates. Fossils obtained from boulders in a coarse layer about 30 feet below the top of bed 8 include *Symphysurina* sp., *Stenopilus* sp., *Hystricurus* sp., and *Pseudagnostus* sp. This layer contained many boulders of white and brown fine-grained limestone, some 4 feet in length. Similar blocks occur in the lower 100 feet of bed 8, but most were unfossiliferous. From one or two such blocks were obtained cf. *Theodenisia* sp., *Plethometopus* sp., ? *Stenopilus* sp., ? *Symphysurina* sp., and *Rasettia* sp.

All these trilobites except ? *Symphysurina* are known from the Levis conglomerate boulders of Upper Cambrian age, but of the fossils from the higher level only *Stenopilus* occurs in the same Levis boulders. *Symphysurina* and *Hystricurus* are Lower Ordovician in age, and the suggestion is that the material forming the conglomerate is of about this age and was laid down during this time.

Bed 8 also crops out between Tucker's Cove and Little Cove and along the shore between the sand bar linking the peninsula to the mainland and Shoal Cove (Fig. 2). Above bed 7 on the southeast side of Tucker's Cove is 8 feet of limestone conglomerate of small chips, succeeded by about 85 feet of thin-bedded brown limestone with shale partings. Southwest of here, at the base of the sand bar, continuous exposures of higher beds are seen. The alterations of coarse boulder conglomerates, flat pebble conglomerates, shales, and limestones with shale partings have been subdivided for convenience (Figs. 2, 3). The contrast in lithology between the sections in beds of the same age at opposite ends of the peninsula shows how rapidly lateral variations may occur. Bed 8a is a coarse conglomerate with many boulders of mottled white and light-gray fine-grained limestones up to 2 or 3 feet in length, and a few chert boulders. Few fossils were found in these boulders; among them were trilobite fragments representing ? *Bellefontia* sp. Trilobites from one boulder in the second conglomerate above bed 8a, here called 8e, include the Upper Cambrian Levis boulder genera *Keithiella*, *Rasettia*, *Leptopilus* and cf. *Onchonotus*; from three or four large boulders a number of typical Canadian genera included:

Trinodus sp.
cf. *Protopresbynileus*
asaphid
remopleuridid, n. gen.
Petigurus sp.
illaenids (2 species)
aff. *Goniophrys*
Ampyx sp.
cf. *Glaphurina*
? *Selenoharpes*
pliomerid

From boulders in bed 8g came similar Canadian trilobites:

cf. *Protopresbynileus*
aff. *Benthamaspis*
illaenid
Ampyx sp.

and from the shale partings in the limestones below (bed 8f) the graptolites

Dictyonema sp.
Clonograptus flexilis (Hall)
C. rigidus (Hall)
Tetragraptus approximatus (Nicholson)
T. quadribrachiatus (Hall)
Phyllograptus ilicifolius Hall

These graptolites are those of the earliest Levis shales, Raymond's (1914) zone A, and are older than any known in the type Deepkill section (Ruedemann, 1947, p. 281, 313). In Australian terms they seem to be of high Lancefield age, approximately equivalent to zone La3 (Harris and Thomas, 1938). The trilobites from 8e are clearly older than this but cannot be closely compared with those from Utah or Nevada described by Ross (1951) and Hintze (1952). Judging by trilobites in older and younger conglomerates, those from 8e are probably from a horizon within the Ross-Hintze zones B to E. Unfortunately the exact position from which *Clonograptus flexilis* came in the Logan, Utah, area (Clark, 1935) is unknown. The cranidium listed as cf. *Glaphurina* sp. is remarkably like that of *G. ? insolita* recently described by Tjernvik (1956) from the early Arenig of Sweden. The general aspect of these trilobites from bed 8e is of a post-Tremadoc age, and accordingly they and the *Tetragraptus approximatus* graptolite zone are regarded as of early Arenig age.

Bed 9 is best seen at the southwest tip of the peninsula, between Point of Head and The Ledge. It includes thin-bedded limestones, shales, and lenses of limestone conglomerate. Near the base, just above the great thickness of conglomerates forming Point of Head, shale partings in dense limestones yielded *Clonograptus* cf. *rigidus* (Hall), *Tetragraptus approximatus* (Nicholson), and *T.* cf. *quadribrachiatus* (Hall).

These beds are of about the same age as bed 8f in Cow Cove but higher beds there, shale partings in thin limestones immediately below the coarse conglomerate bed 9, contain *T. approximatus*, *T. quadribrachiatus*, and *Ptilograptus* sp. These latter are regarded as the basal part of bed 9 in this vicinity. On the west side of Shoal Cove a normal fault trends northwestward (Fig. 2), and west of it are black and gray shales interbedded with limestones, underlying 6 feet of coarse limestone conglomerate. The shales contain the graptolites *Tetragraptus approximatus* (Nicholson), *T. quadribrachiatus* (Hall), and *Didymograptus* cf. *hirundo* Salter. These shales also represent the basal part of bed 9. In the upper part of bed 9 near The Ledge *T. quadribrachiatus* and *Dictyonema* sp. occur in shale partings.

Bed 10 is a coarse conglomerate 4–8 feet thick where it crops out on the north side of the Ledge and up to 20 feet thick where it runs along the low cliff in Shoal Cove. At this latter place some rounded or flat boulders up to 10 feet in length consist primarily of fine-grained limestone. Some boulders are of interbedded shale and limestone. Fossils collected from two boulders included ? *Trinodus* sp., a ribbed asaphid pygidium, cf. *Protopresbynileus* sp., ? *Petigurus* sp., *Ampyx* sp., a raphiophorid, n. gen., and cf. *Ectenonotus* sp. A large collection was also made from a loose boulder on the shore, on the east side of Shoal Cove and near the place where bed 10 appears to be displaced by a normal fault. This boulder may be from bed 9 or bed 10, probably the latter. It contained *Protopresbynileus* sp., a remopleuridid, n. gen., cf. *Petigurus*, *Bolbocephalus* sp., an illaenid, aff. *Benthamaspis* sp., cf. *Psalakilus* sp., aff. *Goniophrys* sp., *Ampyx* sp., a harpid, and a pliomerid.

Comparisons with Ross' (1951) and Hintze's (1952) work suggest that the trilobites from bed 10 and the loose block may be from a zone approximately the same as their zones G and H. Bed 10 could not be recognized in the shales and limestones exposed in the next cove southwest of Shoal Cove. Immediately overlying bed 10 at Shoal Cove and The Ledge are layers of black chert which are weathering brown, followed by shales and thin limestones. From the shale just above the chert at The Ledge came *Dichograptus octobrachiatus* (Hall), *Goniograptus thureaui* (McCoy), *Tetragraptus fruticosus* (Hall), *Didymograptus* of *extensiform* type, and *Phyllograptus* cf. *anna* Hall. In Shoal Cove the shales yielded *Tetragraptus fruticosus* (Hall), *T. serra* (Brongniart), and *Phyllograptus* sp.

These beds are thus of the same age as Raymond's (1914) zone B of the Levis shale, the lowest part of the Deepkill shale (zone 1 of Ruedemann, 1947, p. 61), and the lower part of the Bendigo Series of Victoria, Australia (Harris and Thomas, 1938).

Bed 12 consists of about 20 feet of coarse limestone conglomerate, well exposed on the

east side of Jim's Cove and as it runs out to The Ledge. At the latter locality, as the base is followed landward, it transgresses downward over the thin limestones and shales of bed 11, cutting across 15 feet of stratigraphical thickness in 30 yards along the strike (shown in part in Pl. 1, fig. 2). Several boulders at least 10 feet in length are seen near the base of this bed and give the appearance that this conglomerate plowed into the underlying shale as it was being laid down. Fossils from one boulder in bed 12 at The Ledge include an agnostid, *Nileus* sp., an illaenid, *Telephina* sp., and *Kawina* cf. *vulcanus* (Billings).

Nileus and *Kawina* appear in strata of the Whiterock Stage (Cooper, 1956) in Nevada, and *Nileus* and *Telephina* are well known from the Table Head Series of the same stage (Raymond, 1925, p. 65–66, 83–85), as well as from younger rocks in Virginia. The type species of *Kawina, K. vulcanus* came from the enormous boulder of white limestone in the conglomerate at Lower Head, which is probably the same as the conglomerate layer on Cow Head that is here called bed 14. The age of these trilobites seems to be earliest Middle Ordovician, *i.e.*, Whiterock Stage.

The highest beds on Cow Head peninsula are the shales and thin limestones of bed 13 and the conglomerate on either side of Deep Cove, bed 14. Black shales 3 feet below the base of bed 14 on the west side of Deep Cove contained *Tetragraptus* cf. *serra* (Brongniart), *Goniograptus* sp., *Didymograptus* sp., *Isograptus caduceus* cf. *maximo-divergens* Harris, and *Trigonograptus* cf. *ensiformis* (Hall).

This fauna is like that of Raymond's (1914) zone D_1 of the Levis Shale, the highest Deepkill Shale, and late Castlemain or early Yapeen Series of Victoria, Australia. *T.* cf. *serra* and *I. caduceus* were also found in the folded limestones and shales of bed 13 visible at low tide in Jim's Cove. The conglomerate of bed 14 is 30–50 feet thick. Large blocks of white and of brown limestone, including one of white limestone 75 feet in length and one 20 feet long of limestone and shale may be seen, especially on the west side of Deep Cove. Numerous blocks of this latter type are contorted, with ragged edges projecting into the surrounding fine-grained matrix and pebbles (Pl. 6, fig. 1). From several boulders of gray limestone the following fossils were obtained: *Nileus* sp., *Presbynileu* sp., *Remopleurides* sp., an illaenid, *Bathyurellu* sp., *Ampyx* sp., *Raymondaspis* sp., a harpic a ceraurid, and *Ectenonotus* cf. *westoni* (Bi' ings). From a single boulder of white limesto was collected "*Illaenus*" cf. *tumidifrons* Bi' ings, cheirurid cf. "*Cheirurus*" *prolificus* B ings, and "*Lichas*" *jukesi* Billings.

These last three species are similar to identical with, those described by Billings fron the gigantic boulder of white limestone at Lower Head, in a conglomerate believed to be of the same age as bed 14. The assemblage from bed 14 is typical of the Table Head Limestone. (*Cf.* Schuchert and Dunbar, 1934, p. 68–69.) Whittington collected species of *Ectenonotus* and *Nileus* from the *Orthidiella* zone of the type Whiterock Stage in Nevada. In terms of Ross' (1951) and Hintze's (1952) work in Utah and Nevada this assemblage has some affinities with their highest zones, M and N, but may be somewhat younger than zone N.

St. Paul's Inlet

St. Paul's Inlet (Fig. 1) may be entered through a narrow channel in the relatively wide mouth immediately south of St. Paul's Point—the Outer Tickle. A narrow entrance, the Inner Tickle, leads from a shallow bay into the inlet proper. A section (Fig. 5*B*) is exposed along the inner, east side of the northern promontory forming the Inner Tickle and is the upper part (units 14–27) of that measured

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PLATE 5.—ORDOVICIAN BEDS AT MARTIN POINT AND LOWER HEAD

FIGURE 1.—North of hogback forming point south of Martin Point. Thin-bedded Lower Ordovician limestones and shales overlain by disturbed beds of similar type which pass upward into conglomerate.

FIGURE 2.—Limestone conglomerate at Lower Head resting above shale (at *A* in Fig. 8).

PLATE 6.—ORDOVICIAN CONGLOMERATE, COW HEAD AND LOWER HEAD

FIGURE 1.—Edge of block of folded thin-bedded limestone, in conglomerate bed 14, west side of Deep Cove, Cow Head peninsula. Hammer lies across boundary between block and surrounding conglomerate of smaller pebbles.

FIGURE 2.—Limestone conglomerate on west side of point of Lower Head.

FIGURE 1

FIGURE 2

ORDOVICIAN BEDS AT MARTIN POINT AND LOWER HEAD

FIGURE 1

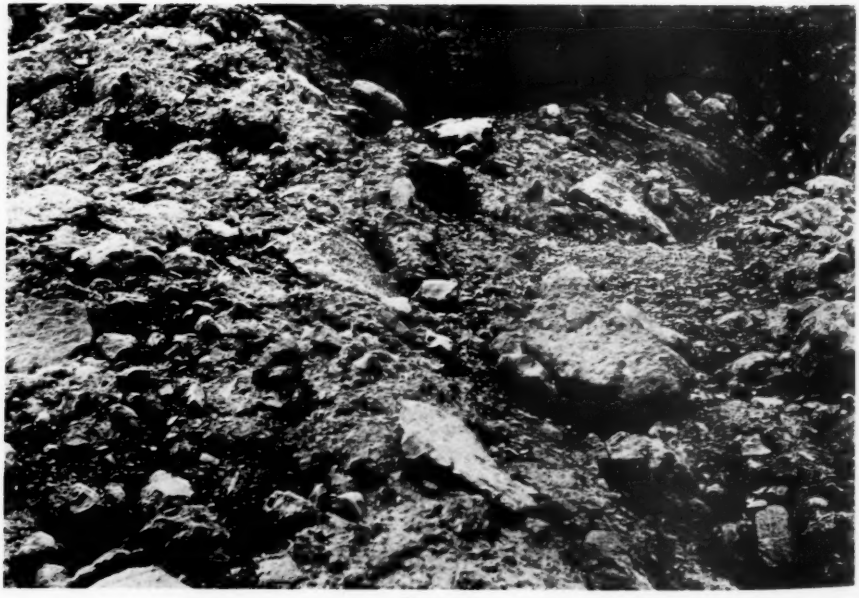

FIGURE 2

ORDOVICIAN CONGLOMERATE, COW HEAD AND LOWER HEAD

FIGURE 1

FIGURE 2

CONTEMPORANEOUS DEFORMATION AT GREEN POINT

FIGURE 1

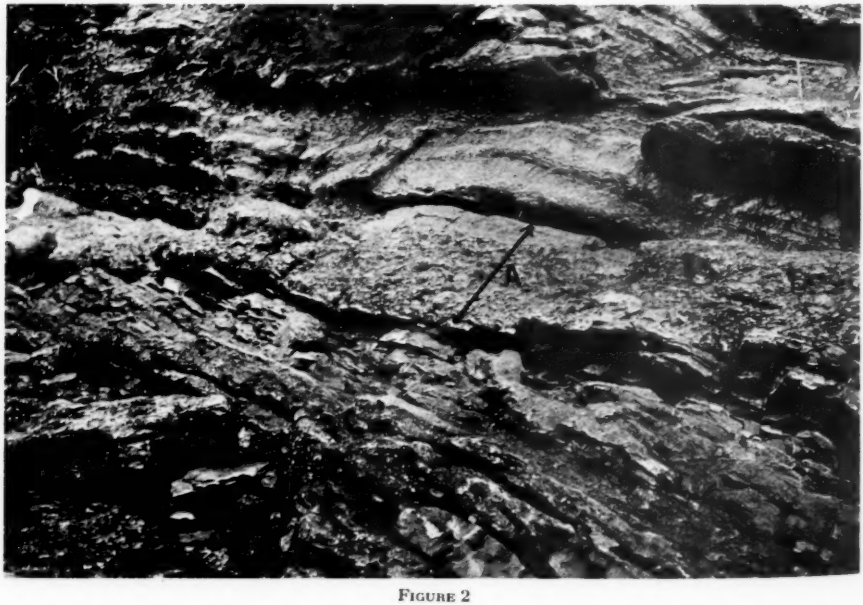

FIGURE 2

MIDDLE CAMBRIAN BEDS AT BROOM POINT

Oxley (1953, p. 22–24). Graptolites were collected at the following points, which are indicated on Figure 5*B*:

(1) From dark shales interbedded with cherts resting on limestone conglomerate (Oxley's unit 14): *Clonograptus rigidus* (Hall), *Tetragraptus approximatus* (Nicholson), and *T. quadribrachiatus* (Hall). These graptolites are characteristic of Raymond's (1914) zone A of the Levis Shale, and of the upper Lancefield Series of Victoria, Australia (Harris and Thomas, 1938).

(2) From dark shales succeeding a conglomerate band, about 80 feet above (1): *Tetragraptus fruticosus* type with three stipes, *T.* cf. *serra*, *Phyllograptus typus*, and *Didymograptus "bifidus"* cf. Ruedemann (1947, Pl. 54, fig. 15). The occurrence of *T. fruticosus* with apparently only three pendant stipes (not four as in the typical form) suggests a correlation with the upper half of the Bendigo Series of Australia (Harris and Thomas, 1938). Specimens identified as *D. bifidus* occur in zone 2 of the Deepkill Shale (Ruedemann, 1947) and in zone C of the Levis Shale (Raymond, 1914).

(3) From a point 24 feet higher in the section, in thin-bedded limestones with shale partings, *Didymograptus protobifidus* of the type illustrated by Decker, 1941, occurs. This graptolite is present in the high Canadian (Decker, 1941) and in the lower Chewton Series of Australia (Harris and Thomas, 1938), the upper part of the *extensus* zone of the British Arenig Series (Elles, 1933), and the upper part of the Lower Didymograptus Shale of Norway (Monsen, 1937).

(4) From shales interbedded with limestones 80 feet higher in the section: *Tetragraptus serra*.

(5) From shales interbedded with limestones containing small brachiopod and trilobite fragments, 75 feet higher in the section (Oxley's unit 26): *Isograptus caduceus* cf. var. *victoriae* Harris, *I. caduceus* cf. var. *maximo-divergens* Harris or var. *armatus* Ruedemann, and *Didymograptus* sp. From the limestones Oxley (1953, p. 22) records the Table Head trilobite, *Endymionia schucherti* Raymond, and a large linguloid brachiopod. The graptolites are characteristic of the Castlemain Series of Australia (Harris and Thomas, 1938).

Kindle collected graptolites at two localities near Black Brook (Fig. 5*A*). At the tip of the point west of the mouth of Black Brook he found *Dictyonema* sp., *Clonograptus flexilis* (Hall), *Phyllograptus* cf. *ilicifolius* Hall, and *Didymograptus* sp. *Phyllograptus* is abundant, and the extensiform didymograptids are large. *Bryograptus* is absent. The assemblage is thus like that of the *Tetragraptus approximatus* zone rather than that of the zone below.

In dark shales interbedded with green sandstones and red shale, just west of the mouth of Black Brook and about 275 feet higher in the section, were found *Isograptus caduceus* cf. var. *divergens* Harris, *Tetragraptus* cf. *bigsbyi*, and *Didymograptus* sp.

The variety of *I. caduceus* indicates a correlation with the highest graptolite-bearing shales of Cow Head peninsula, Martin Point and Lower Head, here considered to be of Whiterock age. These graptolites are of special interest because they date the beginning of deposition of the green sandstones in St. Paul's Inlet. At Martin Point and Lower Head the Cow Head Group is overlain by considerable thicknesses of green sandstone from which fossils have not been obtained. At Cow Head the sandstones are not exposed. It seems likely that in the Cow Head area these green sandstones are late Whiterock, or immediately post-Whiterock in age. Similar green sandstones succeed beds of Table Head age in the Port au Port peninsula and at Table Head (Schuchert and Dunbar, 1934, p. 72–73).

Green Island (Fig. 1, *A*) between the Outer

PLATE 7.—CONTEMPORANEOUS DEFORMATION AT GREEN POINT

FIGURE 1.—Two thin limestone beds contorted by submarine sliding, interbedded with undisturbed shales. Upper part of section at Green Point.

FIGURE 2.—The same beds (as in Figure 1), showing surfaces. In upper layer the sharp crests of folds have fractured.

PLATE 8.—MIDDLE CAMBRIAN BEDS AT BROOM POINT

FIGURE 1.—Bed *A* in left foreground, conglomerate bed *C* forming cliff (Fig. 7).

FIGURE 2.—Fossiliferous conglomerate bed *A* overlain by fossil-bearing bedded limestones of bed *B* (Fig. 7). Lowest conglomerate bed is in foreground.

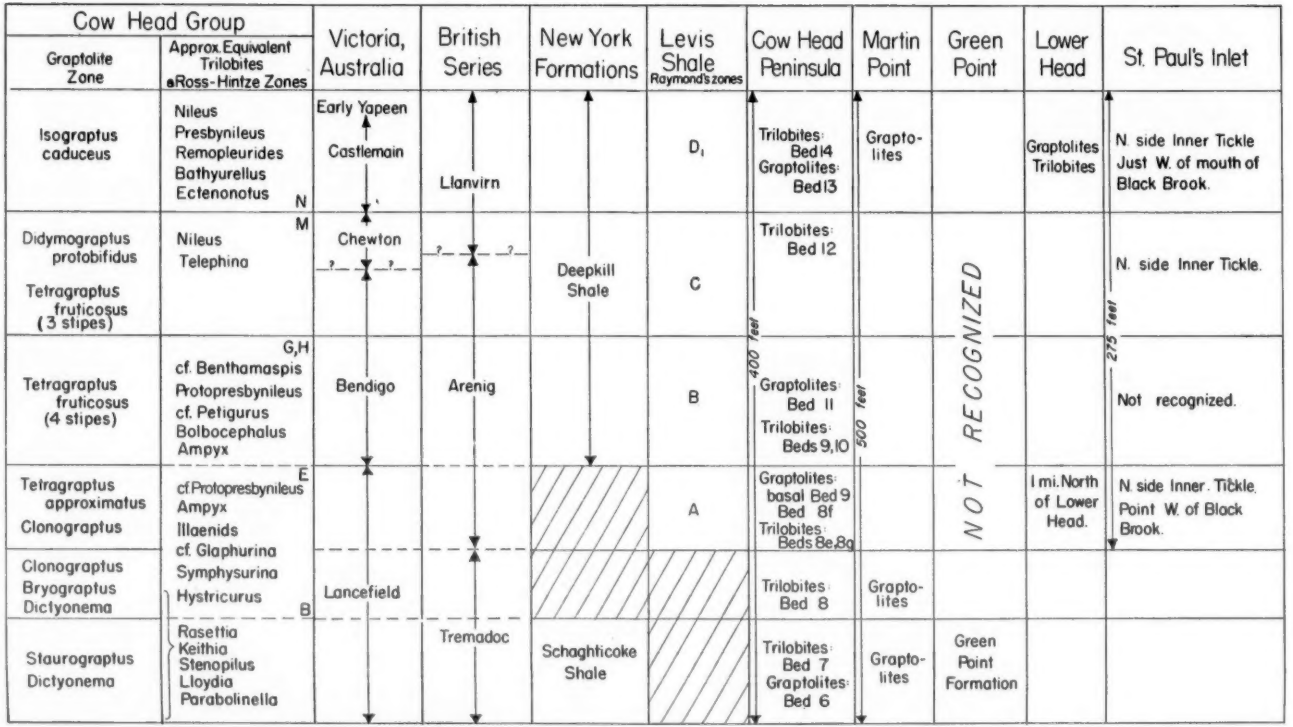

FIGURE 4.—ORDOVICIAN OF COW HEAD REGION AND ITS CORRELATION

and Inner Tickles was revisited, but no fossiliferous boulders were found in 1955. Here an anticline plunging southward furnished John-

Another limestone conglomerate examined in 1955 was that making up White Point on the south shore of St. Paul's Inlet (Fig. 1, *D*). Here

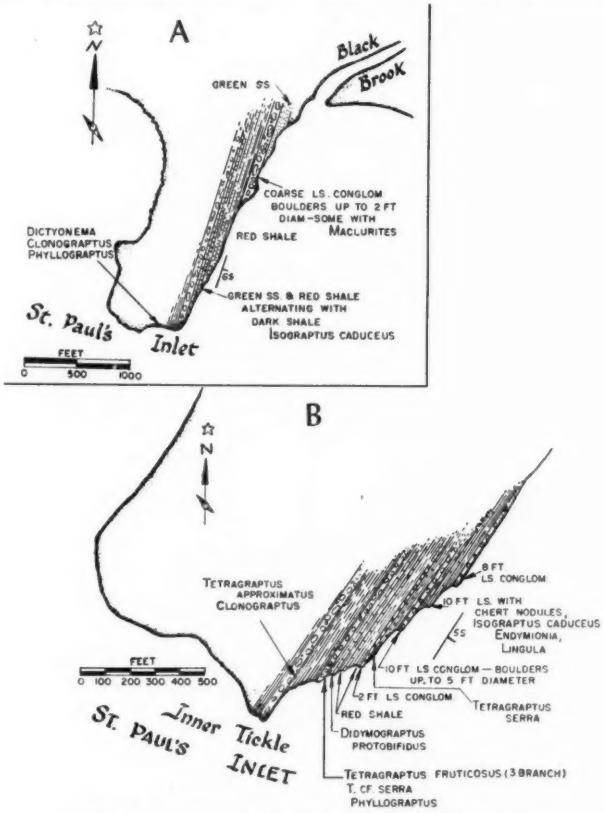

FIGURE 5.—ORDOVICIAN SECTIONS, ST. PAUL'S INLET

A shows upper portion of the Cow Head Group interbedded with overlying green sandstone; *B* shows upper portion of the Cow Head Group on the east side of the Inner Tickle.

son's Geological Survey of Newfoundland party two boulders in 1938 which yielded:

Ctenopyge sp.
Bayfieldia ulrichi
Rasettia sp.
Zacompsus sp.
Stigmametopus sp.
Punctularia sp.
Apatokephaloides sp.
Phylacterus sp.
Richardsonella sp.
Plethometopus sp.
Onchonotus sp.
? *Bellaspidella* sp.

This is a late Cambrian fauna, comparable to that of bed 6 on Cow Head.

two fossil-bearing boulders were found. One contained a large pygidium which seems to be *Orria*. This Middle Cambrian genus has not been found previously east of the Rocky Mountain area. The other boulder contained the middle Cambrian genera *Alokistocare* and *Zacanthoides*. This is an older fauna than any on Cow Head peninsula. It is comparable to that found on the White Rock Islets and to the oldest fauna at Broom Point. This indication of a Middle Cambrian age for this conglomerate is of interest because Johnson in 1938 assigned a Lower Cambrian age to the sandstones exposed in the next small stream to the east (at the base of the falls from the Precambrian cliff).

Martin Point

The beds exposed at Martin Point and their thickness are indicated in Figure 6. The oldest beds are exposed along the north face where seven beds of limestone conglomerate are interbedded with dark shale and limestone. The conglomerate beds are 2 to 8 feet thick and consist of a mixture of flat fragments and rounded boulders. Fossils were found in the rounded boulders, mainly in those of white limestone but also in those of brown, as well as in fine-grained mottled green and white limestone. The fossils include *Keithiella, Pseudagnostus, Hungaia, Loganopeltoides, Theodenisia, Loganellus, Aposolenopleura, and ? Phylacterus*. This is the *Hungaia magnifica* fauna of the Upper Cambrian boulders of Levis and is equivalent to the fauna from bed 6 at Cow Head.

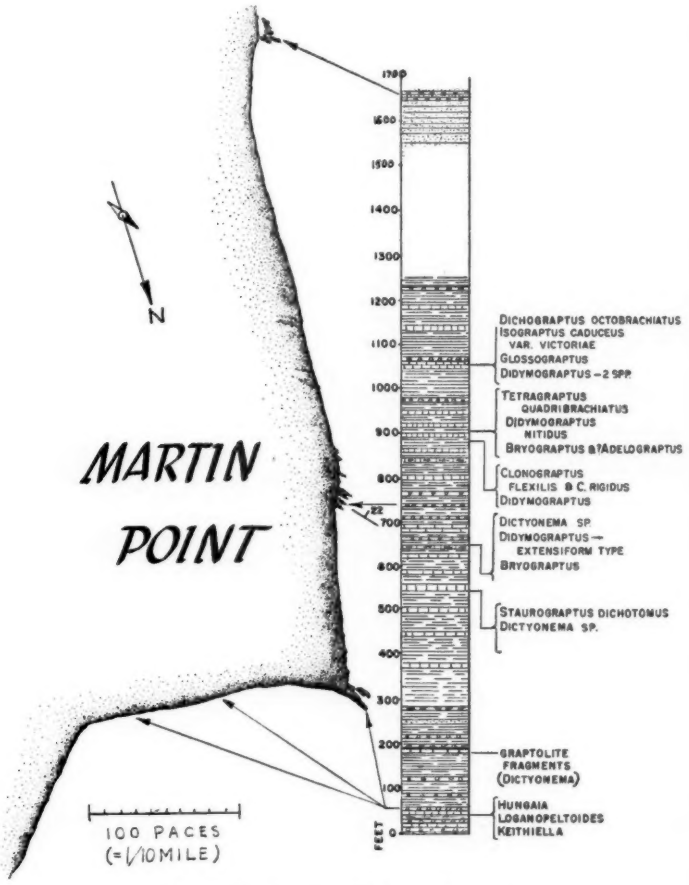

FIGURE 6.—SECTION AT MARTIN POINT

The graptolites *Staurograptus dichotomus* and *Dictyonema* sp., representative of the Green Point Formation, were found 550 feet above the base of the section.

Above this, slumped beds 1–2 feet thick which grade up into overlying limestone conglomerate were noted in thin limestones and shales. Bent pieces of this type of limestone and many flat slabs were seen in the overlying conglomerate (Pl. 5, fig. 1). A similar 1-foot-thick zone of slumped beds was seen below the

lowest limestone conglomerate bed on the north side of Martin Point.

On the north side of the hogback forming a point a quarter of a mile south of Martin Point, 650 feet above the base of section, were found *Dictyonema* sp., *Bryograptus* sp., and *Didymograptus* sp. of extensiform type.

On the south side of the hogback point, 890 feet above the base of the section, were found *Dictyonema* sp., *Clonograptus flexilis*, *C. rigidus*, and *Didymograptus* sp. of extensiform type.

Twelve feet higher in the section were found: *Tetragraptus quadribrachiatus*, *? Adelograptus* sp., *Bryograptus* sp., and *Didymograptus* cf. *nitidus*.

The absence of *Tetragraptus approximatus* from both these higher graptolite-bearing shales suggests that they may be a little older than zone A of the Levis Shale (Raymond, 1914), and that they are pre-Deepkill Shale but post-Schaghticoke Shale. A similarity between this assemblage and that of the middle Lancefield of Victoria, Australia (Harris and Thomas, 1938), is evident.

Higher in the section are several hundred feet of interbedded thin limestone and shale, dark and with some purple and green bands. Two beds of limestone conglomerate, each about 3 feet thick, form conspicuous ribs on the shore. Dark gray and muddy green limestones 20 feet below the second limestone conglomerate yielded *Isograptus caduceus* cf. var. *victoriae* Harris, *Dichograptus octobrachiatus* (Hall), two extensiform species of *Didymograptus*, and *Glossograptus* sp.

This assemblage is about the same age as that found beneath the conglomerate at Lower Head, in the highest shales on Cow Head, and in the highest beds in the section on the north side of the Inner Tickle, St. Paul's inlet. At some of these places *I. caduceus* of the *maximodivergens* or *divergens* type occur, and following Harris' (1933) discussion, one might assume that these faunas were slightly younger than those with variety *victoriae*. However, both varieties occur together in the Inner Tickle section, and hence only a general equivalence of these highest beds of the Cow Head Series with Ca_2 or Ca_3 of the Castlemain Series of Victoria (Harris and Thomas, 1938) can be suggested. In the upper Deepkill Shale (Ruedemann, 1947, p. 350–353) and zone D_2 of the Levis Shale (Raymond, 1914), varieties of *I. caduceus* are apparently not so conspicuous as they are in Newfoundland. Nevertheless, the upper Cow Head Group is of about this age.

Oxley (1953, p. 13) recorded *Isograptus* from this section, and *Staurograptus dichotomus* apparently only a short distance below it. This latter record seems to be in error.

Green Point

About 400 feet of beds, dipping southward at 70°, are exposed at Green Point (Pl. 3, fig. 2), 6 miles south of Martin Point. Most of the upper half of the section is dark shale, with some thin limestones and green and red shales, with silts and sands in the higher part. In the lower half more limestones are present, and there is a conspicuous 4-foot bed of limestone conglomerate near the point. The lowest few tens of feet of beds on the north side of the point are thin-bedded dark-brown, bituminous shales which weather light gray and have interbedded limestones up to 1 foot thick. Certain bands of the bituminous shales are crowded with graptolites, including *Dictyonema flabelliforme* s.l. (with rhabdosomes up to 15 cm in length and 15 cm wide), *Staurograptus dichotomus* Emmons, *Anisograptus* cf. *richardsoni* Bulman, *A.* cf. *matanense* Ruedemann, and *Bryograptus* sp. Species of *Dictyonema*, *Staurograptus*, and *Anisograptus* have been listed from here by Ruedemann (1947, p. 59; *in* Schuchert and Dunbar, 1934, p. 40). This shale is evidently of about the same age as the Schaghticoke Shale of New York and the shales of Matane and Cap-des-Rosiers (Bulman, 1950). No fossils were found above these lower shales, except for unidentifiable fragments of graptolites just above the 4-foot band of limestone conglomerate. Thus the writers could determine no upper age limit to the section at Green Point, and a Green Point Formation (or Series or Group) based on this section (Schuchert and Dunbar, 1934, p. 38) is too vaguely defined to be of use. We therefore limit the term Green Point Formation to beds bearing the graptolites mentioned above.

In the section above the 4-foot conglomerate layer two thin limestone beds are thrown into folds probably as a result of contemporaneous sliding (Pl. 7, figs. 1, 2). The crests of the folds in the higher limestone are broken, but the separate pieces are not dissociated. Dissociation of such fragments might provide the curved pieces of limestone and thin, flat pebbles seen in so many of the limestone conglomerates. Figure 1 of Plate 5 shows similarly disturbed beds passing upward into conglomerate.

Stearing Island

Stearing Island includes a small, outer arc and a longer and wider inner arc, which makes up the island proper (Fig. 1). The writers were able to make only two visits to these islands, with insufficient time to examine all the outcrops even hastily, particularly since the southwestern part of the inner island is accessible only at low tide. The outer arc is apparently formed by a single layer of conglomerate. From boulders there the writers obtained the Middle Cambrian trilobites *Olenoides*, *Solenopleura*, *Parasolenopleura*, and *Welleraspis*.

This appears to be an older fauna than any found on Cow Head. Its age relative to the Middle Cambrian of the White Rock Islets and of Broom Point is yet to be settled.

On the larger island more than one coarse conglomerate band may be seen. Conglomerates of small, flat limestone chips and layers of dark shale with interbedded limestone are present. The succession dips southeastward in the eastern part of the island and southward in the western part. The curved outline of the island reflects this change in strike. From coarse limestone conglomerates on the northwestern, outer shore came boulders containing *Hystricurus* sp., *Symphysurina* sp., aff. *Pareuloma* sp., cf. *Parahystricurus* sp., cf. *Petigurus* sp., and ? *Psalakilus* sp. These trilobites are like those of the lower zones of Ross (1951) and Hintze (1953), and of bed 8 on Cow Head.

The conglomerate that runs along the southeastern side of the island is about 30 feet thick; some of the boulders are 10 feet in length. Trilobites from boulders in this conglomerate include cf. *Pseudagnostus* sp., cf. *Protopresbynileus* sp., aff. *Goniophrys* sp., *Nileus* sp., *Carolinites* sp., *Illaenus* sp., *Telephina* sp., *Glaphurina* sp., *Remopleurides* sp., a cheirurid, and several new genera.

Some of these species are identical with those in beds 9 and 10 of Cow Head peninsula, whereas *Nileus* and *Telephina* are characteristic of beds 12 or 14 of this succession. *Ectenonotus* and "*Lichas*" were not found, however, and it does not seem that any of the boulders on Stearing Island are as young as some of those of bed 14. This conglomerate is underlain by dark-gray shales with interbedded limestones, but only unidentifiable graptolite fragments were found in the shales.

The writers believe that interbedded conglomerates and shales similar to those of Cow Head are exposed on Stearing Island. A fault probably exists between Stearing Island and Cow Head peninsula.

Broom Point

Midway between Cow Head and Martin Point is Broom Point (Fig. 1). The section studied lies between the mouth of Western Brook and the anticlinal cove (Fig. 7). The highest beds are thin-bedded limestones with shale partings; most of the limestone is fine-grained, but some lenses are coarser in grain. Near the top are two conglomerate beds, one about 4 feet thick. From a lens of coarser-grained limestone below this 4-foot conglomerate the writers obtained unidentifiable trilobite fragments and inarticulate brachiopods. From a similar lens at about this level (Fig. 7, *G*) came the Early Ordovician trilobites recorded by Oxley (1953, p. 14–15) and later described by Rasetti (1954). These included *Bienvillia terranovica*, *Borthaspidella gaspensis*, *Leiobienvillia laevigata*, *Pareuloma brachymetopa*, and *P. impunctata*. Oxley (*in* Rasetti, 1954, p. 581) mentions that dark argillites at this locality contain dendroid graptolites, but the writers did not find any. From 50 feet below these highest beds (Fig. 7, *F*), in a limestone conglomerate layer about 10 feet thick (on the south side of the small hill near the outlet of Western Brook), came boulders that contained the following trilobites: *Parabolinella* cf. *triarthroides* Harrington, an olenid, gen. indet., ? *Bellaspis* sp., *Hystricurus* sp., *Plethometopus* sp., *Symphysurina* sp., and *Geragnostus* sp.

Geragnostus, *Symphysurina*, and *Parabolinella* occur in the Morses line slate of Tremadoc age (Shaw, 1951, 1955). *Parabolinella*, *Bellaspis*, and *Plethometopus* are found in the "Upper Cambrian" boulders of Levis (Rasetti, 1944, 1945). These boulders at Western Brook may therefore be Late Cambrian, but the writers believe they are probably Early Ordovician (Tremadoc).

The small hill consists of shale and thin limestones; below these is a considerable thickness of thin and thick beds of limestones (calcarenites and muddy limestones) interbedded with shale and conglomerate layers. Fossils came from two levels in these beds (Fig. 7, *D*, *E*). The second conglomerate north of the hill produced boulders with *Theodenisia* sp., *Plethometopus* sp., *Stenopilus* sp., *Leiocoryphe* sp., *Richardsonella* sp., *Stigmametopus* sp., "*Acidaspis*" cf. *ulrichi* Bassler, and a ? *Ctenopyge* spine. The sixth conglomerate north of the small hill produced a similar fauna in-

cluding *Theodenisia* sp., *Plethometopus* sp., *Stenopilus* sp., and *Leiocoryphe* sp. It seems best to refer these to the Late Cambrian rather than to the Early Ordovician.

Ptychagnostus cf. *praecurrens*, and *Zacanthoides* sp.

This fauna contains a mixture of elements of the Atlantic and Pacific realms. Stratigraph-

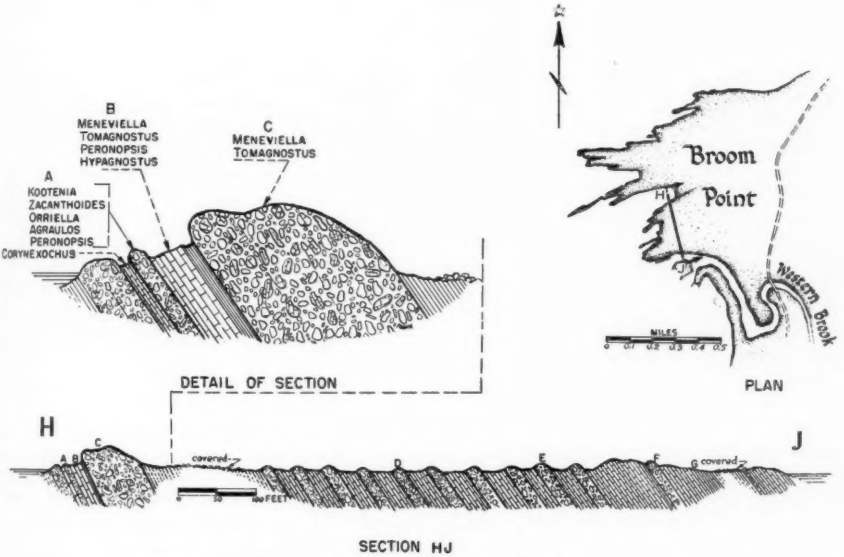

FIGURE 7.—SECTION AT BROOM POINT

H, north end of section in anticlinal cove; J, south end of section at mouth of Western Brook; A–G, fossil localities.

More limestone conglomerate beds, from which no fossils were obtained, occur north and down in the section. Beyond a covered interval is a 50-foot limestone conglomerate bed (Pl. 8, fig. 1; Fig. 7, *C*). Two boulders from this yielded *Meneviella venulosa*, *Solenopleura* sp., *Corynexochus* sp., *Tomagnostus fissus*, *Hypagnostus truncatus*, and *Peronopsis* sp. This fauna is the equivalent of the *Paradoxides hicksi* zone of the Middle Cambrian of southeastern Newfoundland.

Below this 50-foot bed of conglomerate is a 4-foot layer of dark shale which rests on 15 feet of bedded limestone. Near the base of this limestone (Fig. 7, *B*) is a similar fauna (an original find of Oxley) which has *Meneviella*, *Tomagnostus*, *Peronopsis* and *Hypagnostus*.

Below this Middle Cambrian bedded limestone is a 5-foot limestone conglomerate which has yielded many fossiliferous boulders (Pl. 8, fig. 2, *A*; Fig. 7, *A*). Among the trilobites are *Agraulos* sp., *Bolaspis* sp., *Ehmania* sp., *Elrathina* sp., *Kootenia* sp., *Orriella* sp., *Pagetia* sp., *Peronopsis* cf. *fallax*, *Ptychagnostus* cf. *gibbus*,

ically it lies below the Atlantic realm *Tomagnostus-Meneviella* fauna. Whether it also is equivalent to the *Paradoxides hicksi* zone of Newfoundland and the *Paradoxides paradoxissimus* zone of Sweden (Table 2) or is older will be decided by further study of the fauna.

Below this fossiliferous limestone conglomerate is bedded brown granular limestone 3 feet thick. This has furnished a *Corynexochus* cephalon. Below this is a 15-foot limestone conglomerate which has yielded no fossils.

White Rock Islets

Between Cow Head and Lower Head (Fig. 1) is a mile and a quarter of a narrow limestone conglomerate island and underlying beds which is covered in places by waves at times of high tide and wind. Waves and shore currents have built a sand point almost to this island at Downes Point. At the north end only limestone conglomerate can be seen. The lower part of the conglomerate with dolomite (?) blocks seems to be unfossiliferous. The higher part has

boulders up to 2 feet in length of white limestone, brown limestone, coarse oölite, and mottled limestone. Fossils in boulders at the north end include *Orriella* and *Olenoides*. Other Middle Cambrian boulders opposite Downes Point yielded ? *Bathyuriscidella* sp., ? *Ehmania* sp., *Kootenia* sp., ? *Solenopleura* sp., ? *Alokistocare* sp., ? *Glossocoryphus* sp., and *Olenoides* sp.

The *Olenoides* pygidium, which has two long lateral spines, resembles *O. schucherti* from eastern Gaspé. More Middle Cambrian fossiliferous boulders were obtained at the south end of the White Rock Islets, in the upper 30 feet of conglomerates. Below this is 40 feet of conglomerate and dark-brown limestone, poorly exposed and covered by weeds. Lithologically this lower portion is similar to the Arches, an isolated outcrop on the shore 15 miles north-northeast of Cow Head peninsula. There the limestone conglomerate contains some thin slabs of dark limestone but is predominantly made up of a brown granular porous limestone, which is primarily structureless but has a few bedded layers 2 feet thick.

The fossils from the north, south, and central portions of the White Rock Islets show that the islets consist of a Middle Cambrian conglomerate older than any of the beds exposed on Cow Head. They contain trilobites similar to those from boulder bed A at Broom Point. Why the whole Cow Head sequence is not exposed shoreward is not known; perhaps a fault lies southeast of this outcrop.

Lower Head

Observations at Lower Head and along the coast a short distance north are summarized in Figure 8, and an interpretation of the structure is offered in the cross section. At the tip of Lower Head is an unbedded mass of white limestone, which is irregularly fractured and contains calcite-filled geodes. The mass is about 600 feet in length; the scalloped margin is exposed on the west side, where it is in contact with other boulders of this exceptionally coarse conglomerate (Pl. 4, fig. 2). However, along the shore northeast from Lower Head, the mass is replaced by coarse limestone conglomerate; after another covered interval, green sandstones are exposed. Northward along the shore toward the first small cove, conglomerate is exposed and includes several gigantic blocks between 50 and 200 feet in length. One of these is packed with large gastropods (? *Maclurites* sp.). The general appearance of the conglomerates between the large blocks is shown in Figure 2 of Plate 6. Following Schuchert and Dunbar (1934, p. 78–79) the writers interpret the white limestone at Lower Head as a single boulder in the conglomerate. An even larger single boulder in the Levis conglomerate has recently been described by Osborne (1956, p. 187–188).

In the white boulder, fossils occur in concentrated patches, particularly near the geodes. Trilobites are common, and brachiopods and large cephalopods also occur. The writers' collections of 1955 and earlier ones by Kindle include the following trilobites: *Trinodus* sp., **Bathyurellus nitidus* Billings, **B. formosus* Billings, *Goniotelus* sp., *"*Illaenus*" *arcuatus* Billings, **I. tumidifrons* Billings, **I. consobrinus* Billings, *Ischyrotoma twenhofeli* Raymond, *Perischoclonus capitalis* Raymond, an isocolid, a harpid, **Kawina vulcanus* Billings, **Cheirurus mercurius* Billings, and *"*Lichas*" *jukesi* Billings.

Species marked by an asterisk were described by Billings (1861–1865), and the type specimens in Ottawa are all in a white limestone and labelled as from Cow Head. The white limestone is like that of the boulder at Lower Head, and although these specimens could have been collected from a similar boulder in bed 14 on Cow Head peninsula, it seems far more likely that they came from Lower Head. This fauna has usually been regarded as of Chazy age (*e.g.*, Raymond, 1925, p. 166–167), but it may be slightly older, *i.e.*, Whiterock. An upper limit to the age is suggested by the fossils in the black shales and thin limestones on which the conglomerate is seen to rest in the first small cove north of Lower Head (Fig. 8, *A*; Pl. 5, fig. 2). Graptolites in the shales include *Dichograptus octobrachiatus* (Hall), *Tetragraptus* cf. *bigsbyi*, *Phyllograptus* cf. *ilicifolius*, *Didymograptus* sp. of *protobifidus* type and *Isograptus caduceus* cf. var. *divergens* Harris. The presence of *I. caduceus* indicates a high Deepkill or high Levis shale age, or Castlemain of Australia, and thus post-Canadian age. On the opposite (west) side of this cove are black shales, cherts, and thin limestones (Fig. 8, *B*) containing *Dichograptus octobrachiatus* (Hall), *Tetragraptus* cf. *bigsbyi*, *Phyllograptus* cf. *ilicifolius*, *Didymograptus* sp. (wide horizontal stipe), and ? *Isograptus* sp.

These seem to be of the same age, and the writers suggest that they are inverted and underlie the conglomerate immediately to the west. This conglomerate has big blocks of limestone, some of which contain gastropods, and looks like the conglomerate at Lower Head.

Beyond the point made by this conglomerate is a smaller cove, along the west side of which conglomerate crops out. Northward along this outcrop the conglomerate forms a ridge a short distance inland, which runs subparallel to the shore. On the shore black shale, thin limestone, and interbedded cherts are isoclinally folded; they are replaced seaward by outcrops of green sandstone. From the black shales (Fig. 8, *C*) graptolites of Levis shale zone A (or middle Lancefield, La2, of Australia) were obtained. They include: *Dictyonema* sp., *Clonograptus flexilis*, *Tetragraptus approximatus*, *Tetragraptus quadribrachiatus*, *Phyllograptus* cf. *angustifolius*, *Didymograptus* cf. *nitidus*, and *Didymograptus* sp.

The green sandstones are considered to be the same age as those east of Lower Head, *i.e.*, Middle Ordovician, and must be separated by a fault from the contorted black shales and limestones with graptolites.

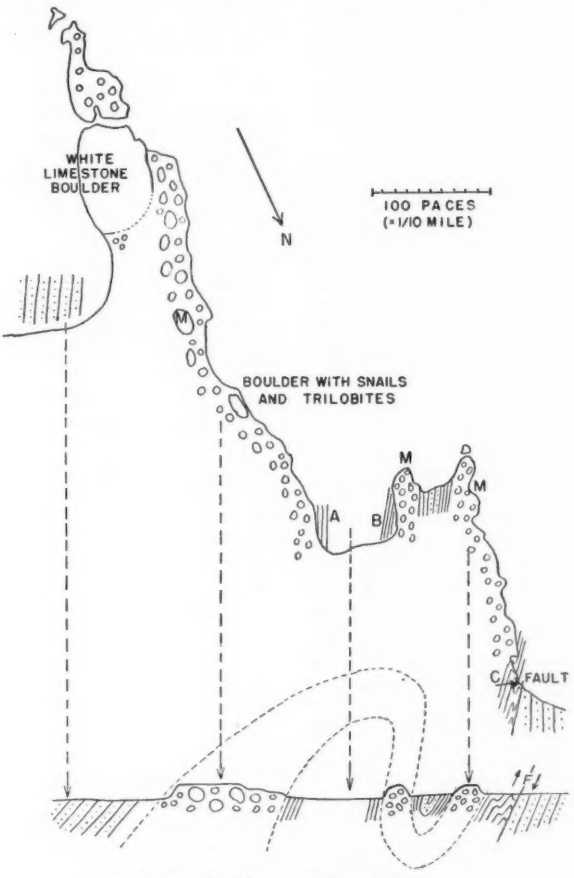

FIGURE 8.—ROCKS OF LOWER HEAD
A, B, C indicate graptolite localities; M represents boulders with *Maduriles* sp.

DISCUSSION OF STRATIGRAPHY

Nomenclature of Cow Head Group

The term Cow Head Group is here used for about 1000 feet of limestones with interbedded shales and limestone conglomerates; the lowest strata are of Middle Cambrian age, the youngest early Middle Ordovician (Whiterock Stage). The name Cow Head Limestone Breccia was

first applied to the exposures on Cow Head peninsula by Schuchert and Dunbar (1934, p. 73). The writers give the name group rank and extend its meaning to include older rocks near the original type exposures. This procedure avoids the introduction of new names, and no name used previously is either as suitable or as readily adaptable. The terminology used here is compared with that of earlier authors in Table I.

Schuchert and Dunbar (1934, p. 38–40) introduced the name Green Point Formation (or Green Point Series) for the shore exposures at Green Point, about 18 miles south southwest of Cow Head. The writers were able to find abundant fossils only in a few feet of shale in the lower part of these exposures; these were of the *Staurograptus-Dictyonema* fauna first made known here by Schuchert and Dunbar. Frequent references have been made to these graptolites (*e.g.*, Ruedemann, 1947, p. 59; Bulman, 1950, p. 67; Dunbar *in* Twenhofel *et al.*, 1954, p. 271), and the writers here limit the name Green Point Formation to the zone yielding this characteristic Early Ordovician fauna. Oxley (1953, p. 12–17) used the term Green Point Group, employing as a standard the sequence of strata from the north face of Martin Point southward about half a mile. We reinvestigated this section (Fig. 6) and believe that it displays beds ranging in age from Upper Cambrian to early Middle Ordovician, *i.e.*, equivalent to a large part of the Cow Head Group. This seems an unwarranted extension of the term Green Point, but the section does include the Green Point Formation as here restricted. Johnson (1941, p. 144) earlier used the term Green Point Group and described the ±1700 feet as "intercalated black to gray shales, sandstones and thin-bedded dolomites or limestones, with breccia." No type section was designated, though this description may refer to the section at Green Point. Unless fossils other than those at the base of the section are found, the group term can hardly be used away from Green Point.

Johnson (1941, p. 143) introduced the term St. Paul's Group, presumably for exposures in St. Paul's Inlet, 600–1000 feet thick, of "black shales, interbedded with thin limestones and sheets of breccia or intraformational conglomerate" containing upper Deepkill and basal Normanskill graptolite faunas. The writers found graptolite-bearing beds from upper Tremadoc (*Clonograptus*) to early Middle Ordovician (*Isograptus*) represented in the two sections examined in St. Paul's Inlet (Fig. 5). Ruedemann's list from "St. Paul's Inlet and other localities" (1947, p. 59) seems to include graptolites from all these beds but no fauna as young as Normanskill. Oxley (1953, p. 17–27) attempted to use the term St. Paul Group for what the writers call the post-Green Point Formation portion of the Cow Head Group, but was unable to work out a zonal sequence of graptolites. It seems clear that such a sequence can be worked out and recognized in different outcrops. A detailed examination of the stratigraphy around the shores of St. Paul's Inlet is necessary before a name based on these exposures can be adequately defined. The name is not used because such information is not available, and because at least some of the rocks in St. Paul's Inlet are of the same age as part of the Cow Head Group.

Johnson (1941, p. 143) also proposed a Western Brook Pond Group, presumably for exposures along the shores of this pond. Johnson states that this group of graywackes, sandstones, black shales, and cherts, 4000–5000 feet thick, yields graptolites of lower Deepkill age. According to Ruedemann (1947, p. 60) the graptolites from these rocks are similar to those of the St. Paul Group. Oxley (1953, p. 18) states that Johnson has abandoned the term Western Brook Pond Group. Again, until the stratigraphy is better known the term can hardly be used or even adequately defined. At the outlet of Western Brook Pond many specimens of *Isograptus* sp. were collected from dark shales in a series of limestones and interbedded dark shales, red and green shales, and limestone conglomerates. Thus at least some of the rocks exposed around the shores of Western Brook Pond are of late Cow Head Group age, as are some of those in St. Paul's Inlet.

The strata underlying the Cow Head Group are not displayed within the region here investigated, nor are the overlying beds seen on Cow Head peninsula. However, at Martin Point, at Lower Head, and in St. Paul's Inlet, beds with *Isograptus* are succeeded by coarse green sandstones. These sandstones were thought to be in faulted contact with the underlying limestone conglomerates, limestones, and shales at Martin Point (Oxley, 1953, p. 13) and Lower Head (Schuchert and Dunbar, 1934, p. 79–80). However, a gradational passage between the two is seen immediately west of the outlet of Black Brook, in St. Paul's Inlet (Fig. 5, *A*). From dark shales interbedded with green sandstones and red shales, and overlying a limestone conglomerate, came the graptolites *Isograptus caduceus* cf. var. *divergens* Harris,

Tetragraptus cf. *similis*, and *Didymograptus* sp. This is the *Isograptus*? fauna of the highest Cow Head Group, and its occurrence at the base of the green sandstones suggests that these sandstones succeed the group in normal sequence. Oxley (1953, p. 34) referred these sandstones to the Humber Arm Group and also thought, with some reservations, that they succeeded the Cow Head Group normally. The present evidence supports the view that the sequence is a normal one.

Schuchert and Dunbar (1934, p. 72–73) tentatively correlated the green sandstones succeeding the limestone conglomerate at Lower Head with the upper Long Point Series. On the basis of the brachipods the Long Point Series is regarded as of Upper Wilderness age (Schuchert and Dunbar, 1934, p. 72; Cooper, 1956, p. 13) or upper Normanskill, far younger than the *Isograptus* beds of Whiterock age. Thus the name Long Point is not used for the sandstones of the Cow Head region, not only because of the difference in age, but also because the Long Point Series is stratigraphically isolated and crops out 95 miles southwest on Port au Port peninsula. The writers do not support Oxley's use of the name Humber Arm for these sandstones. The type section of this series (Schuchert and Dunbar, 1934, p. 86–89) is 60 miles south of Cow Head peninsula; the rocks are shattered and crumpled, and no fossils have been described from the type section (Walthier, 1949, p. 23–26). A new name for these sandstones is not introduced because their stratigraphy is not yet known. Deposition of these sandstones seems to have begun in late (?) *Isograptus* zone time, and Oxley (1953, p. 34) notes the considerable thickness of these clastics. If the Normanskill graptolites recorded by Ruedemann (1947, p. 60, lines 12–21) come from this same series in the neighborhood of Portland Creek Pond (22 miles northeast of Cow Head), then deposition must have continued at least into the Porterfield Stage.

Zonation and Correlation with Other Areas

Suggested zonal divisions of the Ordovician part of the Cow Head Group, occurrence of the zones in various sections, and correlations are summarized in Figure 4. The graptolite zones are broadly conceived on the basis of the succession of faunas recognized, but since the graptolites have been found only in thin beds and interbeds of dark shale, the thickness and limits of each zone cannot be defined. However, approximate total thickness of the sequences is given. Oldest of the faunas is that of the Green Point Formation, found on Cow Head peninsula, at Martin Point, and the type locality. About 100 feet higher in the section at Martin Point are black shales which contain species of *Dictyonema* and *Bryograptus*. Black shales 250 feet higher yielded these fossils and species of *Clonograptus* and ? *Adelograptus*. Neither *Tetragraptus approximatus* nor phyllograptids was found in these strata; hence they probably belong to an older zone than do such layers as bed 8f and basal bed 9 on Cow Head peninsula, which yield *T. approximatus*, abundant phyllograptids, and *Clonograptus*, but not *Bryograptus*. This *Clonograptus-Bryograptus* zone of Martin Point has not been recognized elsewhere, but the *T. approximatus* zone has been found in St. Paul's Inlet and also 1 mile north of Lower Head.

The next graptolite-bearing shale found on Cow Head peninsula (but not recognized in other sections) is that with *Tetragraptus fruticosus* having four stipes. It is a characteristic fauna of the lowest part of the type Deepkill and of Levis zone B (Raymond, 1914). The rhabdosomes of *T. fruticosus* type collected at the Inner Tickle, St. Paul's Inlet, seem to have only three stipes; in the same layers is a species of *Didymograptus* similar to some that have been called *D. bifidus*. Slightly higher in the section *D. protobifidus* is common. These two faunas are placed in a single zone, the three-stipe *T. fruticosus* recalling the higher part of the Bendigo Series of Victoria, and *D. protobifidus* equivalents of the Chewton Series. These two zones have been recognized only in St. Paul's Inlet. In all sections, below the highest conglomerates of the Cow Head Group, are varieties of *Isograptus caduceus* like those of Australia (Harris, 1933). The varieties of *I. caduceus* occur with different assemblages in different places, *e.g.*, with *Trigonograptus* in bed 13 on Cow Head peninsula and with *Dichograptus octobrachiatus* at Martin Point and Lower Head. Also the varieties do not occur in the same sequence in time as in the Castlemain Series of Australia; there *Trigonograptus* appears in the succeeding Yapeen Series (Harris and Thomas, 1938). Thus the *Isograptus caduceus* zone is a broad one, which cannot at present be subdivided, and is evidently equivalent to Raymond's zone D_1 at Levis and the highest part of the type Deepkill shale.

Although the graptolites have been collected from bedded strata, all the trilobites are from conglomerate boulders on Cow Head peninsula or at Lower Head. Comparison with other

areas, and particularly with Ross' (1951) and Hintze's (1952) work in Utah and Nevada, shows that the trilobites from successively higher conglomerates are stratigraphically younger. In addition, the boulders in any particular conglomerate can hardly be much younger than the strata on which that conglomerate rests, though they may be somewhat older. The trilobites listed in Figure 4, then, may be regarded as only approximately the same age as the graptolites shown to correspond. Some interesting points emerge from this tentative correlation. As has been discussed previously, genera known from the Upper Cambrian *Hungaia magnifica* fauna of the Levis boulders occur in conglomerates 50–100 feet above the Green Point Formation; in some boulders they occur with Tremadoc genera. Thus some of these genera may range higher than has been supposed but perhaps not above the middle Tremadoc. Trilobites of middle and upper Lancefield (and also middle and upper Tremadoc) age include some genera that occur in Ross' and Hintze's zones B to E, and also *Ampyx* sp. This genus appears commonly in beds of Porterfield age in North America but was not recorded from the older strata studied by Ross or Hintze. Species do occur in the Lower Ordovician McKay Group of British Columbia (Kobayashi, 1955), and Whittington recognized one in C. W. Merriam's collections from the Ninemile Formation of the Pogonip Group (Nolan, Merriam, and Williams, 1956, p. 27). Some of the genera in the highest conglomerates are common to the Whiterock Stage, and these boulders are derived from rocks that may be the same age as at least part of the *Isograptus caduceus* zone.

The graptolite faunas of the Cow Head Group and New York and Quebec formations are evidently similar, and their likeness to those of the Australian sequence is remarkable. This resemblance is far greater than that to any of the zones of Britain or Scandinavia; the attempt to correlate with Britain raises problems. Harris and Thomas (1938) regarded the Lancefield and Tremadoc as equivalent, but it is suggested, on the basis of the supposedly equivalent trilobites, that the top of the Tremadoc should be placed lower down. A different opinion is also expressed as to the position of the Arenig-Llanvirn boundary. Harris and Thomas placed this boundary well above the Yapeen Series and regard strata with *D. protobifidus* and *Isograptus caduceus* as equivalent to the upper part of the *extensus* zone of the Arenig. This seems to be because both these fossils are known from the upper part of this zone in Britain (Elles, 1933), and because *Isograptus* is abundant at a slightly higher horizon in Norway (Spjeldnaes, 1953). On the other hand, possibly *D. protobifidus* and *I. caduceus* appear earlier in Europe than elsewhere, and the great burst of varieties of *I. caduceus* in North America and Australia may be later, as late as Llanvirn time. The basis for this suggestion lies in the apparent equivalence of Whiterock trilobites (*Nileus, Remopleurides, Bathyurellus, Ectenonotus*) with the *I. caduceus* zone. It seems difficult to accept middle Arenig age for these trilobites and reconcile this with views expressed elsewhere on correlation between the British and North American Ordovician (Whittington, *in* Twenhofel *et al.*, 1954); Llanvirn age seems more probable. Confirmatory evidence that the Whiterock Stage limestones of the Table Head may be of *Isograptus* zone age is offered by graptolites in shale overlying these limestones at Black Cove, about 1½ miles northeast of the gravels at Port au Port peninsula (Schuchert and Dunbar, 1934, Pl. 7, *A*). The collection of these graptolites includes *Didymograptus* sp., *Isograptus* cf. *forcipiformis* (Ruedemann), *Cardiograptus crawfordi* Harris, ? *Skiagraptus*, *Glyptograptus* cf. *dentatus*, and *Glossograptus hincksii* and is of upper Yapeen age, *i.e.*, a zone immediately above the *Isograptus* zone of the highest part of the Cow Head Group. Dunbar (*in* Twenhofel *et al.*, 1954, p. 255) also listed some of these genera from this locality.

The sequence of Cambrian faunas is shown in Table 2. The oldest of these occurs in a 5-foot conglomerate at Broom Point (Fig. 7, *A*). Here are found *Agraulos*, ? *Bolaspis*, *Kootenia*, *Zacanthoides*, *Orriella*, *Peronopsis*, and *Ptychagnostus* cf. *gibbus*. This may be equivalent to the *Ptychagnostus gibbus* zone (B1) of Sweden (Westergard, 1946). In the bedded limestone above this occurs *Meneviella*, *Peronopsis*, *Hypagnostus*, and *Tomagnostus fissus* which must be correlated with the *Tomagnostus fissus* zone (B2) of Sweden and with the *Paradoxides hicksi* zone of southeastern Newfoundland.

The Dresbachian faunas have been interpreted as the equivalent of the *Paradoxides forchhammeri* zone of the late Middle Cambrian (Lochman, 1956; Wilson, 1957). Following this suggestion the writers place the Cow Head Dresbachian in the Middle rather than in the Upper Cambrian. Beds 1 to 4 on Cow Head are then to be correlated with the *Paradoxides forchhammeri* stage of Sweden and more particularly with the *Solenopleura brachymetopa*

zone (C2) if one follows Wilson (1957). Above this is the *Taenicephalus* faunule which is correlated with the *Conaspis* zone of the Franconian of the mid-west and possibly with zone 4 of the Olenid Series of Sweden. The succeeding *Hungaia magnifica* fauna of Bed 6 at Cow Head is to be correlated with zone 5 of the Olenid Series of Sweden because of the presence of *Ctenopyge*.

Relation of Cow Head Group to Other Sequences

Johnson (1941) was the first to recognize the existence of two facies in the Ordovician rocks of this region (Table 1): one of the St. George-Table Head series, the other the types of rocks exposed at Green Point and along the shores of St. Paul's Inlet and Western Brook Pond. Rocks of age equivalent to the Cow Head Group are best known from the Port au Port peninsula, about 105 miles southwest of Cow Head. In this area the sequence includes Middle Cambrian sandstones, shales, silts, and dolomites (Schuchert and Dunbar, 1934, p. 33–35; Lochman, 1938); the fossils come from the upper 750 feet of dolomites and siltstones. Succeeding these beds are about 2000 feet of the St. George Series of dolomites, limestones, sandstone, and siltstone (Schuchert and Dunbar, 1934, p. 45–51). Upper Cambrian fossils have not been discovered in these rocks, and those fossils described from the St. George Series are seemingly from the upper part and of upper Canadian age (*e.g.*, Ulrich *et al.*, 1944, p. 21–22; Whittington, 1953, p. 658, 660–661). The overlying early Middle Ordovician Table Head Series includes about 800 feet of dark-gray limestone with black shale at the top. The Middle Cambrian to Middle Ordovician sequence of Port au Port is thus on the order of 3500 feet thick and consists primarily of dolomites and limestones. This series of rocks forms the coast line from Cape Norman at the Strait of Belle Isle south to Table Head. From there to the Port au Port peninsula it is found a short distance inland (in bays and inlets), discontinuously exposed at the foot of the Long Range (Schuchert and Dunbar, 1934; Walthier, 1949; Oxley, 1953). The lithology is predominantly dolomites and limestones, but the dating of parts of the sequence and of particular exposures in various areas is vague or unknown. Oxley (1953) mapped St. George and Table Head dolomites and limestones as running along the foot of the Long Range 4 or 5 miles east of the type area of the Cow Head Group but identified no fossils to substantiate this dating. Present knowledge indicates that this predominantly dolomite-limestone facies was deposited during the same span of time as the Cow Head Group and attained a thickness 2 or 3 times as great. Whether deposition of this facies was continuous or not is uncertain.

The writers tentatively conclude, then, that to the east of the Cow Head Group facies a limestone-dolomite facies was being deposited during at least part of the same time.

Not enough is known of the thicknesses and distribution of the Cow Head Group conglomerates to guess the geographical position of the area from which the boulders may have been derived. Cambrian and Early Ordovician limestones of the lithological types and fossil content of these conglomerates are unknown in place in western Newfoundland. Some of the upper Canadian and early Middle Ordovician limestone boulders, however, contain fossils identical with those known from the St. George or Table Head Series which crop out 50 miles or more northeast. Possibly deposition in this general area of a third facies, at least in Middle and Upper Cambrian times, supplied the limestones now included in the conglomerates. Conglomerates of the Cow Head Group type (*i.e.*, intraformational in origin) are present in the upper Table Head rocks of the Port au Port area and northward beyond Cow Head to Daniel's Harbour and perhaps even to Pistolet Bay (Schuchert and Dunbar, 1934, p. 81). The limestone conglomerates at Levis, Quebec, and along the south shore of the St. Lawrence contain boulders of Cambrian limestones remarkably similar in lithology and fossil content to those of the Cow Head area. Thus the facies from which these boulders were derived is not a purely local phenomenon but one that extended (not necessarily continuously) about 800 miles along the strike. That these two or three facies were not separated from each other by any great distance or barrier is indicated by examples of their intertonguing—*e.g.*, intraformational conglomerates in the Port au Port area, upper St. George-type boulders in the conglomerates, and the occurrence at Broom Point of bedded limestone with the same trilobites as in the boulders of the overlying conglomerate. It does not seem necessary to suppose that these facies everywhere were deposited in the same geographical relationship to each other, *i.e.*, ran in linear bands along the strike, one always east or west of the other. They might occur sporadically, depending on tectonic, sedimentary, and oceanographic conditions prevailing in particular areas.

Origin of the Conglomerates

Contrary to Schuchert and Dunbar's views, the writers believe the evidence to be conclusive that the conglomerates of the Cow Head Group were not all formed at the same time in direct connection with Middle Ordovician thrusting. Rather, the conglomerates are intraformational and originated at intervals during the long span of time from Middle Cambrian to early Middle Ordovician. They are intercalated within a surprisingly thin (±1000 feet) sequence mainly of limestone and shale, and each layer is about the same age as the strata on which it rests. The conglomerates consist of beds of small, flat chips (Pl. 5, fig. 1) in which there may be scattered large blocks, or of angular and subangular boulders (a few inches to 600 feet in length) in a muddy (rarely sandy) matrix (Pl. 6, fig. 2). Blocks of interbedded limestone and shale, usually folded, may occur (Pl. 6, fig. 1), and rarely lumps of chert, shale or siltstone. Most of the boulders and chips are limestone, and no igneous or metamorphic material was seen. No petrological studies of either the boulders or the matrix were made, and the fossil collections were generally from the larger fragments. This is because such boulders generally project from the weathered surface of exposures, and can be more readily broken, whereas the layers of small chips tend to weather to a smooth surface. Perhaps one in thirty of the larger blocks contain fossils, and it was soon discovered that in any one conglomerate layer, limestones of a certain color or texture were generally unfossiliferous, whereas others were generally the reverse. All this points to the source of the conglomerates being a region of limestone deposition, the limestone varying in color and texture to include calcarenites, oölites, calcilutites, and dense fine-grained, varicolored porcellanous limestones (thin- and thick-bedded), sometimes with shale partings, and also including unbedded masses of light-colored biohermal (?) type. Deposition must have been continuous from Middle Cambrian to Middle Ordovician time, with relatively rapid lithification, in order that the boulders may rest on rocks of similar age.

As has been discussed in the preceding section, the known Middle Cambrian rocks of Port au Port peninsula and parts of the dolomitic Lower Ordovician St. George Series are hardly suitable as a source for the conglomerates, and thus the source limestones may represent a separate facies. This facies cannot have been far distant, not merely because of the size of the blocks but because, for example, in bed 3 on Cow Head bedded limestones pass laterally into conglomerates (Pl. 1, fig. 1), and at Broom Point limestones of the same type as seen in certain boulders directly underlie the conglomerate. It seems necessary that the source area, after deposition and lithification, must have been raised and broken to produce the larger blocks, though the chips might have been produced by slumping and consequent breaking up of thin limestone layers (Pl. 7, figs. 1, 2; Pl. 5, fig. 1). The blocks and boulders must have slid down a submarine slope as King (1951, p. 84) was the first to suggest.

The uneven base of some layers, the wedging out of layers, and the cross-cutting relationship of the base of bed 12 at The Ledge on Cow Head peninsula (Pl. 1, fig. 2), all support this view. Occasionally a boulder seems to have travelled alone, or rolled on ahead of a slide (Pl. 4, fig. 1). The same general mode of origin of the Levis conglomerates has recently been advocated by Osborne (1956, p. 185–187). The writers do not think the boulders in the Cow Head Group came from cliffs of great height because such an origin should provide boulders of a wider stratigraphic range than we find in any one layer. However, a submarine fault of minor displacement could initiate a submarine landslide which would include strata of a limited horizon only.

The direction of movement of the boulders cannot be surmised from the available evidence. It seems at least possible that the limestones were laid down on the crests of sporadically distributed ridges. Presuming these ridges to be elongated in the north-northeast to south-southwest direction of the present strike, sliding off them might have been in either direction—east or west. For the Levis conglomerates Osborne (1956, p. 197–198) prefers an origin from the south, particularly because Late Ordovician thrusting is from this direction. Since the Levis and Cow Head conglomerates seem to be related phenomena, and since the thrusting at the foot of the Long Range in western Newfoundland is from the east, one might go on to assume that the Cow Head conglomerates moved in from the east, as a result of earlier tectonic movements producing linear welts. This may or may not be so, but it seems that the evidence now available is not decisive.

From his observations near Portland Creek, 20 miles north of Cow Head, Nelson (1955, p. 44) was "inclined to attribute the formation of the breccia to localized earthquakes affecting

semi-consolidated limestone muds. These shocks would partially fragment the limestone so as to give an interlocking texture.... Exotics would be considered as fragments of overlying and underlying rocks incorporated in the breccia during its formation."

The nature of the Cow Head Group strata is well explained in an article on Flysch sedimentation by Sujkowski (1957) whose field work was done in the Carpathian mountains of central Europe. A few of his sentences may be quoted:

"The name Flysch is a facies denomination for a marine deposit composed of innumerable alternations of sharply divided pelitic and psammitic layers. Other rocks in the deposit are accidental, and in particular pure limestones are rarely present. The series commonly attain thicknesses of thousands of feet and were deposited in geosynclinal areas. The pelitic layers are composed of either calcareous or noncalcareous shale; the psammitic layers are chiefly sandstone, but mudstones, arkoses, conglomerates, and gravel beds are also found.... If remains of micro-organisms exist in a shale layer neighboring a fossil-bearing psammitic layer, the fossils in the shale differ from those in the psammite and in most cases have siliceous instead of calcareous skeletons. The shell detritus and the foraminifera seem to have been brought with the coarse material from outside the site of deposition.... It was never possible to identify layers from different profiles by their thickness: sandstone beds especially could not be compared even in two profiles across the same tectonic unit 1 mile apart.... the average rate of deposition [of the shale portion is] 0.8–1.0 inches per 1000 years. The average thickness of the individual layers is about 5 inches. Thus a sandy phase occurred about every 4000 years.... The permanently unstable condition of the slope, with slides occurring at more or less regular intervals over millions of years, indicates some tectonic movement in the basin itself, or at least some steady subsidence of the lower end of the slope. Subsidence was uniform rather than rhythmic, but a steady steepening of the submarine slope caused breaks of equilibrium and in consequence submarine landslides at rhythmic intervals.... Each landslide of soft sediment moving down the slope might become a turbidity current; each spread a layer of psammitic deposit at the bottom of the slope and made a future lens of sandstone.... Flysch is a facies characterized by both monotony and variability. The pelitic (monotonous) element represents the indigenous deposit; the psammitic (variable) element is exotic. The nature of the pelitic layers and the required mechanism for the introduction of the psammitic layers make it clear that Flysch was deposited in a deep-water environment."

If the sandstone beds had been limestone conglomerate beds, Sujkowski's description would have fitted the Cow Head Group. It helps explain why fossils other than graptolites are so scarce in the monotonous thin-bedded limestones and shales of the deeper-water deposits but are not uncommon in the boulders which have come down from shallower environments.

Future work alone can determine whether this is a regular stratigraphic sequence of conglomerates unique to this region or is found in other limestone conglomerates of the St. Lawrence valley. It is interesting to see what has been written of the conglomerates and associated beds at Levis and Quebec. Of the Sillery [Charny], Bailey *et al.* (1928) say "the fossiliferous limestone boulders of the Sillery conglomerates are exclusively Cambrian; almost all of them are of Lower Cambrian date." Above the Charny, Osborne (1956) places the Lauzon Formation in which Middle Cambrian fossils have been found in boulders. Boulders from the overlying Levis Formation "include a few of Lower Cambrian and a profusion of Upper Cambrian and Beekmantown date" (Bailey *et al.*, 1928). The younger Quebec City Formation has shales with graptolite faunas of mid-Trenton age and contains fossiliferous boulders of Black River and Lower Trenton age though these fossils "are not of the same character as the fossils found in Canada in these formations northeast [northwest] of the Champlain-St. Lawrence thrust." (Bailey *et al.*, 1928) There seems to be a regular stratigraphic sequence except for the Levis Formation in which "at least nine conglomerates could be distinguished." It would be interesting to know if the mixture of Cambrian and Ordovician fossiliferous boulders occurs in all nine of these conglomerates. Whatever future studies may show of the stratigraphy of the Levis conglomerates their similarity to those of the Cow Head region is striking and their origin may be similar. For the Cow Head Group we concur with Bailey, Collet and Field (1928) in their observation on the Lèvis conglomerates "We hold that the limestones.... of the one facies were intermittently discharged as landslips down a submarine slope on to the muds of the other facies."

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Short Notes

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PLEISTOCENE GLACIATION IN NORTHERN LABRADOR

BY E. P. WHEELER, 2ND

Introduction

Flint (1951, p. 21) has set forth the theory that there were local centers of glaciation on several highlands in eastern North America after they emerged from beneath the general ice sheet. Among such centers he mentions the Kighlakhpait (Kiglapait) Mountains and Khaumayat (Kaumajet) Mountains on the northern Labrador coast.

I have worked on the bedrock geology in the neighborhood of these mountains since 1926, and Flint's paper prompted me to pay particular attention to field evidence bearing on this theory during several trips to the area made since 1951.

I wish to thank Professors O. D. von Engeln and E. H. Muller who read this note and offered suggestions for its improvement; also the British Newfoundland Corporation which provided transporation by air and vessel, making it possible to visit many of the localities mentioned.

The Kighlakhpait Mountains and Khaumayat Mountains are separated from the interior upland by north-south valleys connecting arms of the sea, with divides that do not exceed 500 feet in elevation (Wheeler, 1935, map opposite p. 254). The mountain areas are so small that these valleys should have diverted any ice flowing westward from ice caps centered on the coastal mountains, and any glaciation originating in these areas should have been local and insignificant.

Indicator Erratics

The Khaumayat Mountains are composed of a basic volcanic series overlying Precambrian gneisses, and this volcanic series does not occur elsewhere; it is bounded on the west by a fault along the north-south valley that separates the mountains from the interior uplands. Thus the extent of glaciation originating in the mountains can be measured by the distribution of the dark volcanic erratics.

Careful search over the first gneiss hill southwest of the contact on the isthmus between Horr Harbor and Kai-kai Inlet, Lat. 57° 49.5′ N., Long. 62° 07.0′ W.[1] elevation 400 feet, revealed no erratics of the Khaumayat volcanic rocks though these rocks occur at elevations of 1100 feet within a mile to the northeastward. One medium-grained diabase block was found, but it was much more like a diabase dike that outcropped near at hand in the gneiss than the volcanic rocks to the northeast. Thus the erratics give no indication of westward-moving ice.

On the other hand there is much evidence for eastward-moving ice. Erratics of gray gneiss, amphibolite, and pale garnet-biotite gneiss from the west were found on all traverses in the volcanic rocks. Peter Grimley, who made presumably the first ascent of Mt. Brave, elevation 4150 feet, the highest summit in the Khaumayat Mountains, found such erratics up to an elevation of about 3850 feet. He did not have time to search carefully at higher elevations. However, he could see no change in the form of the summit slopes that might suggest they had not been overridden by the ice that brought erratics from the west to the 3850-foot level. These data are difficult to reconcile with Dahl's (1946, p. 232; 1947, p. 234) view that the maximum slope of an ice sheet surface cannot exceed 1 in 100. This would require that the edge of the ice sheet that overrode Mt. Brave lie 80 miles to the eastward where few soundings of less than 100 fathoms have been recorded.

The pale garnet gneiss is of particular value as an indicator erratic since it is resistant to weathering and is easily detected, and only one formation from which it can be derived is known in the region. This formation occurs in a zone extending from the upper part of Naghvakh (Nachvak) Fiord south to the head of

[1] Position from U. S. H. O. Chart No. 5845, Saglek Bay to Nain, 2d edition, April, 1955

Tessiuyakhsoakh Bay. It lies near the height of land, some 50 miles westward from the line connecting the western flanks of the Khaumayat Mountains and Kighlakhpait Mountains, yet I have found erratics of it out to the coast in all this region.

Westward from the Kighlakhpait Mountains the edge of the interior uplands is composed of anorthosite and adamellite. One of the highest summits of this region is 3390 foot elevation at Lat. 57° 02.8′ N., Long. 62° 25.3′ W.[2] Erratics of the pale garnet-biotite gneiss were found at this summit and a number of other summits in the vicinity as well as on lower ground. This indicates that the last ice to pass over these summits came from the westward. If it had come from the Kighlakhpait Mountains to the east, or if a local ice cap had succeeded the Laurentide Ice Sheet, these erratics from the westward would presumably have been removed from the summits.

Striae and Other Data

In the country west of the Kighlakhpait Mountains all glacial striae in areas where direction of ice movement would be relatively uninfluenced by local topography indicate a general trend of movement from south of west. Friction cracks associated with crescentic gouges demonstrate the motion was not westward. Local divergences from this direction are generally explicable on the basis of the influence that local topography would have on the ice movement. There is a striking correspondence between this direction and the axes of drumlins and drumlinoids plotted on the 8-mile-to-the-inch topographic sheet of the Nain-Nutak area by Douglas and Drummond (1953).[3] Neither the direction of striations nor the drumlins and drumlinoids in the area can be explained on the basis of ice caps centered in the Kighlakhpait Mountains or Khaumayat Mountains. They suggest a general ice movement from the far interior in a direction north of east.

A traverse across the height of land near Lat. 57° 20′ N. and numerous views from the summits west of the Kighlakhpait Mountains indicate that elevations in the divide region are less than those of the summits at the edge of the upland that have been overridden by the ice. Oblique air photos taken after the first snow falls in September indicate no marked difference in the degree of snow cover between the east margin of the upland and the divide region. Thus there is no compelling evidence for postulating that the highest point of the ice sheet that overrode the east edge of the uplands was along the crest of the Atlantic watershed rather than farther in the interior of the Labrador Peninsula.

Conclusions

The field evidence in and around the Kighlakhpait Mountains and Khaumayat Mountains indicates that the only important Pleistocene ice movement of which any trace remains was from south of west, which is in accordance with the alternative theory of Douglas and Drummond (1953, p. 15) that there was a center of glaciation in the Knob Lake region. This corresponds to the conditions outlined by Flint (1951, p. 35) for the time when the Laurentide Ice Sheet had its maximum extent.

There is no field evidence to support Flint's theory that the Kighlakhpait Mountains and Khaumayat Mountains were important ice-cap centers during the waning phases of the Laurentide Ice Sheet.

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[2] Position and height from the writer's unpublished map of the region

[3] Professor Wilson kindly made available copies of the pertinent 8-mile-to-the-inch topographic sheets on which their paper is based

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PLIOCENE VERTEBRATE FAUNA FROM THE BITTERROOT VALLEY, MONTANA, AND ITS STRATIGRAPHIC SIGNIFICANCE

BY R. L. KONIZESKI

Dating and correlation of Tertiary strata in the northern Rocky Mountains are chiefly dependent on fossil vertebrate faunas. The Bitterroot Valley in western Montana is a north-south structural trough, 80 miles long and having a maximum width of 9 miles. Tertiary sedimentary rocks whose indicated age has heretofore been based on a small, stratigraphically inadequate collection of vertebrate fossils described by Earl Douglass (1909, p. 264, 265) partly fill the valley. Douglass spent considerable time in 1889, 1901, and 1905 exploring the east side of the Bitterroot Valley but found only a few fragmentary specimens. These included the distal portion of a *Procamelus* ulna-radius, a small piece of mastodon tooth, and some tooth fragments "which belonged to the high-toothed type of later Miocene horses" (Douglass 1909, p. 265). He concluded that the upper (east-valley) beds were Miocene and that some of the lower (central-valley) beds were of Oligocene age.

The genus *Procamelus* has since been shown to have ranged into the Pliocene (Simpson, 1945, p. 150). The fragmentary, nonspecific nature of Douglass' specimen detracts materially from its value as a stratigraphic index, other than on a questionable generic basis. The piece of mastodon tooth and fragments of horse teeth are equally nondefinitive, for the same reason. Subsequent to Douglass' explorations, local residents collected two fossil vertebrate faunas and gave them to the Department of Geology of Montana State University. These collections have, unfortunately, been lost, but Dr. C. F. Deiss, who was with the department at that time (1935), stated (Personal communication) that "the bones were so fragmentary that identification [age] was a guess as to Pliocene".

The Tertiary geology of the east side of the Bitterroot Valley was studied in 1956 in the course of a geologic and ground-water investigation by the U. S. Geological Survey. During the investigation a careful search was made for fossils in order to determine the stratigraphic and structural relationships of the Tertiary rocks. The following assemblage was collected.

Pseudaplodon cf. *P. occidentale*	Clarendonian
Mammut Pliomastodon cf. *P. matthewi*	Clarendonian
Pliohippus interpolatus	Clarendonian?-Hemphillian
Teleoceras cf. *T. fossiger*	Clarendonian-Hemphillian

Family APLODENTIDAE

Pseudaplodon cf. *P. occidentale* McDonald

U.S.N.M. 21616 Right M_3 partially worn but with pattern clearly visible. Specimen collected from brick-colored clays on north bank of unnamed arroyo immediately north of Willow Creek, sec. 36, T. 7 N., R. 19 W., Ravalli County, Montana. This specimen and the type (from the Truckee Formation, lower Pliocene, of western Nevada) are the only recorded specimens.

Family MAMMUTIDAE

Mammut Pliomastodon cf. *P. matthewi* Osborn

U.S.N.M. 21617 Plaster cast of newly erupted left M_1 of specimen collected in 1952 by Mr. S. Eldrick from gray alluvial sands at base of a section along Willoughby Creek, north bench of Willoughby Creek, sec. 9, T. 8 N., R. 20 W., Ravalli County, Montana.

U.S.N.M. 21618 Molar fragments, this species by association, from same locality as above.

U.S.N.M. 21816 Fragmental M_3?, collected from gray ash clays on south drainage of Ambrose Creek, sec. 16, T. 9 N., R. 19 W., Ravalli County, Montana.

Family EQUIDAE

Pliohippus interpolatus Cope

U.S.N.M. 21619 Newly erupted left M_3, collected from buff-colored silts on north bank of Willoughby Creek, sec. 16, T. 8 N., R. 19 W., Ravalli County, Montana.

U.S.N.M. 21620 Left P_3 collected from buff-colored fanglomerates exposed along Three Mile Creek, sec. 26, T. 10 N., R. 19 W., Ravalli County, Montana.

U.S.N.M. 21621 Right M_2 collected from gray ash clays exposed along Ambrose Creek, sec. 16, T. 9 N., R. 19 W., Ravalli County, Montana.

Family Rhinocerotidae

Teleoceras cf. *T. fossiger* Cope

U.S.N.M. 21622 Lingual half of right M^2 with protoloph and metaloph, left metatarsal, and cervical? rib, collected in association from buff-colored clay exposed along Ambrose Creek stratigraphically above the gray ash clays of N. M. 21621, sec. 16, T. 9 N., R. 19 W., Ravalli County, Montana.

The dip of the Tertiary beds in Bitterroot Valley is generally valleyward and to the north. It decreases westward from 5°–6° in the east-valley marginal areas to less than 1° in the flat-lying beds of the central-valley area. Lithologic changes and an extensive Pleistocene cover make it difficult to trace any single bed in its entire cross-valley extension. It appears, however, on the basis of structural relationships, that less than 200 feet of Tertiary section is exposed. The sedimentological and fossil distributions indicate stratigraphic equivalency of all the visible sediments. The individual and collective stratigraphic ranges of the interred fossil vertebrates are conclusive evidence of an early Pliocene, Clarendonian age.

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SONORASPIS AND *ALBERTELLA* IN THE INYO MOUNTAINS, CALIFORNIA

BY ALEXANDER STOYANOW

This paper essentially deals with two stratigraphically and paleogeographically important index trilobites, one characteristic of the Middle Cambrian fauna of Canada and the other of Mexico; their presence and relative position in the sequence have been recently established in the part of the Inyo Mountains widely known in literature since Walcott's classical studies on the Cambrian geology of America.

The presence of *Sonoraspis* in the Marble Mountains and Bristol Mountains northeast of Los Angeles was reported in two Short Notes on certain Middle Cambrian trilobites of California (Stoyanow and Susuki, 1955; Stoyanow, 1956). Therefore the find of *Sonoraspis* closely associated with the strata containing *Albertella*, made by Mr. and Mrs. R. Saul in the Inyo Mountains under direction of Professor C. A. Nelson, is of special interest since it indicates a more northern occurrence of *Sonoraspis* and the approximate relation of the Arrojos Formation, Sonora, and the Cadiz-Bonanza King Formations, California, to the Middle Cambrian of the Canadian Rocky Mountains (Stoyanow, 1957).

In the southern part of the Cordilleran Cambrian trough, in Sonora, a species of *Albertella*, *A. proveedora* Lochman (1952, p. 137, Pl. 23, figs. 1–8), occurs at 100 and 625 feet above the base of the Arrojos Formation (Cooper and Arellano, 1952, p. 20; Lochman-Balk, 1956, p. 533). Another species, *A. schenki* Resser (1945, p. 181, 195, Pl. 20, fig. 18), described from the Bright Angel Formation of the Grand Canyon, was collected 252 feet above the *Olenellus* zone. These two trilobites, with short semicircular or slightly angular pygidia, are regarded as sufficiently different from *A. bosworthi* Walcott (1908, p. 22, Pl. 1, figs. 5, 6; 1917, p. 38, Pl. 7, figs. 3, 3c) and *A. helena* Walcott (1908, p. 19, Pl. 2, figs. 1–4; 1917, p. 39, Pl. 7, figs. 5, 5a), respectively, to warrant a specific separation. On the other hand, the example of *Albertella* from the Inyo Mountains, discussed and illustrated here, is closely affiliated and possibly even conspecific with one of two species that have long and broad pygidia as described by Rasetti (1951, p. 154, 155) from the *Albertella* zone of the Cathedral Formation, locality C15n, Bow Lake, Alberta.

Consequently, the presence in the Inyo Mountains of *Sonoraspis* and *Albertella*, both closely related to the described species, may well serve as a preliminary indication of a station marking a contact between the Canadian and Mexican basins of the Cordilleran seaway. From the stratigraphic standpoint it is important to note that, according to Rasetti (1951, p. 109), in the Canadian Rockies the *Glossopleura* zone, with *G. boccar* (Walcott) and *G. merlinensis* Rasetti, is above the *Albertella* zone. In the Grand Canyon, too, the zone of *G. mckeei* Resser and *Anoria tontoensis* (Walcott) is approximately 145 feet above the stratum with *Albertella schenki* Resser, whereas a small specimen of *Anoria* (?) was collected 42 feet below the same datum. (McKee, 1945, p. 30, 33). Since Lochman (1952, p. 180) does not recognize *Sonoraspis* and equates it with *Glossopleura* both stratigraphically and paleontologically, the exact relation of the strata with *Albertella* to those with *Sonoraspis* and *Glossopleura* (if present) in Sonora is not clear. Cooper and Arellano (1952, p. 6, fig. 5, columns C and D), following Lochman, place *Albertella* beds between the strata jointly marked as *Glossopleura-Sonoraspis* both below and above. It has been pointed out elsewhere (Stoyanow and Susuki, 1955, p. 468) that the presence of *Glossopleura* in Sonora has not been established, and that all four specimens with eight-segmented thorax, described and illustrated as *Glossopleura* by Lochman (1952, p. 135, Pl. 31, figs. 8, 9, 12, 14), belong in *Sonoraspis*. However, in a recent publication (Lochman-Balk, 1956, p. 532, Fig. 1) the stratigraphic position of *Glossopleura*, without appended *Sonoraspis*, is indicated considerably above that of *Albertella*—that is, as in the Canadian Rocky Mountains, in the Grand Canyon, and, according to Deiss (1938, p. 1162, Fig. 7), in several parts of the Cordilleran trough in Wyoming, Utah, Nevada, and northwestern Montana.

Therefore, it deserves attention that in the Inyo Mountains Mr. Saul collected *So-*

noraspis nelsoni, sp. nov., about 20 feet *below* the stratum with *Albertella* aff. *stenorhachis* Rasetti collected there by Mrs. Saul. Assuming the correctness of data as presented above, the writer's earlier suggestion (Stoyanow, 1952, p. 52) that the strata with *Sonoraspis* may be stratigraphically older than those with *Glossopleura* seems to have certain potentialities. The types of *Albertella* aff. *stenorhachis* and *Sonoraspis nelsoni* are described here. Description of a form of *Ogygopsis*, collected by Professor Nelson very low in the Cambrian sequence, is added.

Albertella aff. *stenorhachis* Rasetti

(Plate 1, figure 1)

The specimen of *Albertella* from the Inyo Mountains is a pygidium comparable to the pygidia of *A. stenorhachis* Rasetti (1951, p. 155, Pl. 18, figs. 18–21), a species based exclusively on pygidia which, nevertheless, are of specific distinction since, according to Rasetti, they cannot be confused with the pygidia of other described species of *Albertella*.

This specimen is especially close to the holotype of Rasetti's species illustrated as his Figure 18 of Plate 18. It has the same configuration with a remarkable proportion of the parts in which, though the length of the pygidium and its maximal width at the anterior margin are equal, the gradual backward convergence of lateral sides resulting in a narrow and subtruncated posterior border, and tapering of the axis of 6 beadlike segments with a terminal section, gives an impression of an elongate rather than an equidimensional pygidium.

Differences between the described specimen and Rasetti's holotype are as follows: (1) The spine issuing from two anchylosed anterior segments is not at an angle to the axis, as it is in Rasetti's type, in which only its proximal part is preserved, but is parallel to the axis almost to the level of the axial furrow separating the 6th segment from the terminal section, at which level the sides of the spine rapidly converge into a sharp point. It seems, however, that in the paratype of Rasetti's species, Figure 21 of his Plate 18, there is an impression of the broken distal part of the spine; if true, this would also indicate a spine parallel to the axis. In this case, however, the spine would be fused with the lateral side of the pygidium for a considerable length, much as in the pygidium of *A. limbatum* Rasetti (1951, p. 154, Pl. 18, figs. 11, 17). (2) The axial segments of a more rapidly tapering axis are not so narrow longitudinally as in *A. stenorhachis* and are not expanded laterally. (3) The size of the Alberta and California types is considerably different: the length of the pygidium in the holotype of Rasetti's species is a little more than 10 mm., whereas in the described specimen it is 33 mm.; consequently, the California original is approximately as large as the figure of Rasetti's holotype.

Type: Figured specimen closely related to *A. stenorhachis* Rasetti, UCLA, Pal. Coll. Cat. No. 28992.

Occurrence: Waucoba Mtn. Quad., Inyo County, California, in a gray oölitic limestone about 20 feet above the stratum with *Sonoraspis nelsoni*.

Sonoraspis nelsoni, sp. nov.

(Plate 1, figure 3)

The holotype of this species (Pl. 1, fig. 3A) is a complete specimen except for the free cheeks. It has eight untuberculated thoracic segments and lacks a macropleural development as in *S. torresi* Stoyanow (1952, p. 53, Pl. 14, figs. 1–4) but differs by the facial suture which is as in *Glossopleura*. Another distinctive feature is the glabella with subparallel sides and a front more rounded than in certain forms of *Glossopleura* species (Walcott, 1916, Pl. 52, figs. 1a, 1b; Pl. 53, figs. 2a, 4). The setting of thoracic segments and the pygidium

PLATE 1.—*ALBERTELLA, OGYGOPSIS, SONORASPIS*

All figures are unretouched photographs

FIGURE 1.—*Albertella* aff. *stenorhachis* Rasetti. Figured specimen. UCLA, Pal. Coll., Cat. No 28992. Note the long pointed spine parallel to the axis. × 1 46.

FIGURE 2.—*Ogygopsis klotzi* (Rominger)? Figured specimen laterally compressed. UCLA, Pal. Coll., Cat. No. 28990. Note the pygidium with unfurrowed pleural lobes. × 1.86.

FIGURE 3.—*Sonoraspis nelsoni*, sp. nov. × 1. (A) Holotype. UCLA, Pal. Coll., Cat. No 28991. Showing the untuberculated eight-segmented thorax and facial suture. (B) Paratype? UCLA, Pal. Coll., Cat. No. 28993 Partially preserved cranidium and thorax.

Figure 1

Figure 2

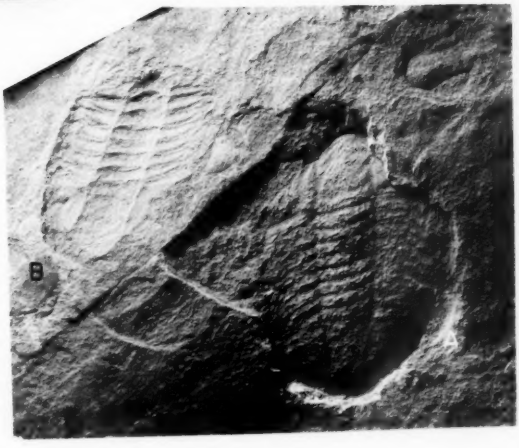

Figure 3

ALBERTELLA, OGYGOPSIS, SONORASPIS

with a narrow border considerably resemble a type from Utah illustrated by Walcott (1916, p. 369, Pl. 53, fig. 2c, U.S.N.M. No. 15456c) as *Dolichometopus productus*, the presence of the eight thoracic segments in which was mentioned in the generic discussion of *Sonoraspis* (Stoyanow, 1952, p. 50–51). In the paratype? (Pl. 1, fig. 3B), the posterior part of the thorax and the pygidium are not preserved.

Type: Holotype: UCLA, Pal. Coll., Cat. No. 28991; Paratype?: UCLA, Pal. Coll., Cat. No. 28993.

Occurrence: Waucoba Mtn. Quad., Inyo County, California, in a light-brown sandstone about 20 feet below the stratum with *Albertella* aff. *stenorhachis*.

To facilitate identification of *Sonoraspis* species Table 1 is presented.

Ogygopsis klotzi (Rominger)?

(Plate 1, figure 2)

Among the species falling within the compass of *Ogygopsis* Walcott, a genus not as yet reported either from Sonora or from the Grand Canyon but occurring in the Inyo Mountains, of special interest both paleontologically and stratigraphically are those in which the pygidia deviate from that of the genotype by the lack of furrows on the pleural lobes and by the substitution of an uninterrupted pygidial border by one partially or completely wavy or denticulated.

The described examples of such forms are *Taxioura magna* Resser (1939, p. 62–63, Pl. 14, fig. 1), the figure of which shows a spine and probably reduced denticulation in the right anterior part of the pygidial border, and *Ogygopsis spinulosa* Rasetti (1951, p. 192, Pl. 21, fig. 4) in which denticulation of the pygidial border is complete. The stratigraphic position of the Canadian species is tentatively correlated with the lowermost faunule of the *Albertella* zone (Rasetti, 1951, p. 95, 96). As to the position of *Taxioura* in the Ptarmigania strata of the northern Wasatch Mountains, the reader is referred to the comments of Rasetti (1951, p. 95). It appears, however, that in either case the corresponding species are more or less associated with the *Albertella* zone. Therefore the find by Professor Nelson of the specimen discussed in this Note several hundred feet below the strata with *Sonoraspis* and *Albertella* is significant.

The equal length of the axis and the entire pygidium was regarded by Resser (1939, p. 62, Pl. 14, figs. 1, 10, 12, 14; Shimer and Shrock, 1944, p. 617, Pl. 259, figs. 23–24) as most characteristic for his genus. In the pygidium of the genotype of *Ogygopsis*, *O. klotzi* (Rominger, 1887, p. 12, Pl. 1, fig. 1) the axis is represented as appreciably shorter than the length of the pygidium, and the same interrelation was interpreted in a sketch by Woodward (1902, p. 530, fig. 1), whereas in the illustration by Walcott (1916, p. 377, Pl. 66, fig. 1) the partly broken terminal section of the axis seems to be closer to the border. Rasetti (1951, p. 191, Pl. 12, figs. 2–5; Pl. 21, figs. 1–2; Pl. 29, figs. 7–8) has shown as *O. klotzi* both the forms with a shorter pygidial axis and those in which the axis reaches the border.

Since various names have been applied to the furrows associated with the pleural lobes of *O. klotzi*, a brief summary of the used terms is relevant. Rominger (1887, p. 13, Pl. 1, fig. 1) gave the following description of the pleural lobes in the genotype:

". . . costal expansions which dilate considerably toward the margin, and bear in place of the central depression of the free ribs a rounded central ruga bordered on each side by a furrow; the edges of anchylosed ribs are likewise indicated by an elevated rim."

This condition is not adequately represented in his diagrammatic figure but can be easily interpreted from the right side of the pygidium illustrated by Walcott (1916, p. 377, Pl. 66, fig. 1). Although he did not elaborate on the description of the pygidium of *Ogygopsis*, Walcott (1916, p. 380, Pl. 66, fig. 2) rendered a fine description of pleural lobes in the related genus *Orria*:

"The pleural lobes are broad and marked by eight broad, shallow furrows and a posterior pair that appear to come out of the posterior section of the axis; each broad furrow is separated from those adjoining by two narrow, sharp ridges with a narrow furrow between them that represents the anchylosed line of separation of the original segmentation now united to form the pygidium."

Howell *et al.* (1947, p. 75) recommended *Interpleural groove* to indicate the position of the fused segments of the pleural lobes of the pygidium and *Pleural furrow* as a groove extending transversely across each fused segment of the pleural lobes. Resser (1939, p. 62), describing *Taxioura*, had used the terms *Pleural furrow* and *Pleural groove*; the latter obviously

TABLE 1.—SPECIFIC DIFFERENCES IN DESCRIBED SPECIES OF *Sonoraspis*, INVARIABLY WITH EIGHT THORACIC SEGMENTS AND WITH MIXED FEATURES OF *Anoria* AND *Glossopleura*

Species	Thoracic tuberculation	Macropleural development	Facial suture	Reference
S. torresi	None	None	As in *Anoria*	Stoyanow (1952)
S. gomezi	Present	None	As in *Glossopleura*	Stoyanow (1952)
S. californica	Present	None	As in *Anoria*	Stoyanow and Susuki (1955)
S. mohavensis	None	5th and 6th segments	As in *Anoria*	Clark (1921); Resser (1928); Stoyanow (1956)
S. nelsoni	None	None	As in *Glossopleura*	Sp. nov., this paper

is equivalent to *Interpleural furrow* of Rasetti (1951, p. 192).

The specimen illustrated in Figure 2 of Plate 1 has unfurrowed pleural lobes; an axis which does not extend to the border; the latter is linear with an interrupted outline, and whether its margin is denticulated or wavy is difficult to say because of weathered condition.

Rasetti (1951, p. 191) does not regard *Taxioura* Resser as a valid genus since it differs from *Ogygopsis* only by unfurrowed pleural lobes. It appears, however, that the species and forms discussed above, except for the genotype of *Ogygopsis*, have one feature in common—that is, unfurrowed pleural lobes. It also appears that this group ranges up to the *Albertella* zone or, possibly, as Resser held, slightly beyond it. It would not be amiss to mention in this connection that *Ogygopsis*, the only trilobite previously reported from the Middle Cambrian of the Inyo Mountains by Knopf and Kirk (1918, p. 32), was identified by Walcott only as "*Ogygopsis* sp. near *O. klotzi*."

Type: Figured specimen questionably placed under *Ogygopsis klotzi*: UCLA, Pal. Coll., Cat. No. 28990.

Occurrence: Several hundred feet below the strata with *Sonoraspis* and *Albertella*, Waucoba Mtn. Quad., Inyo County, California.

I wish to express my thanks to Professor Nelson and to Mr. and Mrs. Saul for the loan of interesting specimens and for the information on their stratigraphic setting.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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MINERALOGY AND PETROLOGY OF THE CURRANT CREEK MAGNESITE DEPOSITS AND ASSOCIATED ROCKS OF NEVADA

New Data

By George T. Faust and Eugene Callaghan

In 1948 the authors described the minerals and rocks of the Currant Creek area (Faust and Callaghan, 1948). Further studies have occasioned this note.

The authors referred to a "dolomite-magnesite solid-solution series" and indicated that further work would be necessary to characterize this mineral. Faust continued studies on this mineral and in 1953 described it as the new mineral, huntite, $Mg_3Ca(CO_3)_4$. The 1948 paper should be changed as follows:

Page	*Line*	*For*	*Read*
19	Item A-1007(a) Table 1	a dolomite-magnesite solid solution	huntite
42	5	delete lines 5 through 18	
44	7	the dolomite-magnesite solid-solution mineral	huntite
44	10	the dolomite-magnesite solid solution	huntite
44	18	the dolomite-magnesite solid-solution mineral	huntite
44	25	fine-grained carbonate solid solution	huntite
53	3	dolomite-magnesite solid solution	huntite
68	last line	the dolomite-magnesite solid solution	huntite
69	11	a mineral of the dolomite-magnesite solid solution series	huntite
51	Fig. 3	dolomite-magnesite solid solution	huntite
54	Fig. 6	dolomite-magnesite solid solution	huntite

Huntite has also been found at the north end of the Longyear Exploration Drift in the 1800 level of the Chief Consolidated mine, Eureka, Utah, by T. S. Lovering (Faust, 1953, p. 6); at the Dorog mine, Dorog, Hungary, by Koblencz and Nemecz (1953); and by Baron and others (1957) in the grotto of l'Hérault (la Clamouse), France, where it is found as montmilch (rock milk).

On page 29, line 14, "less orthoclase" should be "less albite".

During the petrologic work on the 1948 paper, the authors looked for welded tuffs at Currant Creek, but the criteria for recognizing them were meager at that time. Clarence S. Ross and Robert L. Smith of the U. S. Geological Survey have been working on establishment of criteria and on other petrologic problems of the welded tuffs. Smith visited the Currant Creek area in 1953 and on the basis of his field observations thought that the rock described as a porphyritic quartz latite was a welded tuff. Subsequent examination of our original thin sections has confirmed this view. Accordingly, the name porphyritic quartz latite, given on pages 46–49, should be modified to read "welded tuff having the composition of a quartz latite".

The following references pertinent to the theoretical discussion on the physical chemistry of the formation of magnesium silicates were found too late for inclusion. (*See* pages 64–65.) Gjaldbaek (1925), in determining the activity-product constant of magnesium hydroxide, found that the solutions of magnesium hydroxide attacked the glassware so strongly that he was forced to line all glass parts with paraffin to prevent reaction. Billheimer and Nitardy (1936) also found that milk of magnesia (magnesium hydroxide) when stored in glass bottles at summer temperatures (100°F) attacks the glass and develops excess alkalinity. These date support the theory proposed for the decomposition of volcanic glass by magnesium-rich solutions.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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USE OF PUNCHED CARDS TO SPEED STATISTICAL ANALYSES OF GEOMORPHIC DATA

MARK A. MELTON

Geologists are finding hand-sorted punched cards increasingly useful as aids to geologic research and development in those branches of the science that require extensive sorting of information obtained from hundreds or thousands of observations. The main function of the punched-card records, as heretofore used, is to provide a convenient, permanent index for cross-referencing various classes of data and making comparisons. The systematization and examination of many data can usually be accomplished in a remarkably short time (Finch, 1957). Though such use may be termed "statistical," the writer is convinced that punched cards are even more useful in studies involving more elegant statistical methods.

In contrast to the reference-file use of punched cards, they have been used variously to facilitate computations in statistical analyses of quantitative data (Miller and Weller, 1952; Melton, 1957). The purpose of this note is to enlarge on the methods the writer used in correlation and regression analyses of geomorphic data, in hopes that other research workers may find them similarly useful.

Sets of cards were prepared for use in correlation and regression analyses of a fairly large number of variables then discarded when the studies were completed; the coding system was tailored to fit the particular samples on hand. By using a set of cards enough times to offset the initial investment of labor in preparing them, a substantial saving can be made over the time required to complete statistical analysis of the same data by conventional methods. This is because ordering sorting, and counting, operations readily performed with the cards, are substituted for inspecting and copying numbers in tabulated form and, in certain cases, for actual calculations.

Climatic, surficial, ecologic, and geomorphic measurements were taken in drainage basins in mature topography; 16 variables were considered. For a pilot study, a method was needed for finding, as rapidly as possible, the pairs of variables that showed significant statistical correlation and the pairs that appeared to lack correlation. Data from each drainage basin of the sample were entered on a card in the form of punches around the margin. A field of 5 to 10 spaces was allotted to each variable, and classes of equal intervals were defined to cover adequately the range of sample values and so that the spaces of the field were in one-to-one correspondence with the classes (direct coding; Casey and Perry, p. 277). For example, the mean valley-side slope, θ, ranged from about 5° to 38° in the particular sample available. A field of eight spaces was allotted to that variable, and a class interval of 5° chosen. The class 0.00°–5.00° corresponded to the first space of the θ field, and all basins whose mean valley-side slope fell between those limits had its card punched at that place. The class 5.00°–10.00° corresponded to the second space of the θ field, and so on to 35.00°–40.00° which corresponded to the eighth space (Fig. 1). A similar scheme was devised for each of the other 15 variables.

After all pertinent information available about each drainage basin had been recorded on its card, correlation (parametric) and regression analyses of pairs of variables were made by grouped-data methods, employing correlation tables as described by Croxton and Cowden, (1941, p. 673 ff.). The frequency in each cell of a correlation table for two variables was found by sorting groups of cards according to the space punched in the field of the first variable, then sorting each of these groups in the same way for the second variable. In this manner, about 25 correlation tests were completed in much less time than would have been required with standard techniques. Sample sizes ranged from 23 to 132, but there was little difference in the time required for computation; the additional time was only that needed to count the additional cards.

Because of data grouping, indicated standard errors were higher than would have been obtained with ungrouped data, and correlation coefficients were correspondingly lower. Increasing the size of the field allotted to each variable and decreasing the class interval would tend to correct this, but the number of spaces in each field is limited by the size of the card used and the number of variables considered. When every space on the card must be utilized fully, a compromise should be reached by considering the interest attached to each variable and the objectives of the study. A

more efficient method of coding might be used to increase the number of classes without enlarging the field correspondingly (*e.g.*, selector coding; Casey and Perry, p. 278), but the direct coding method explained above (1956, p. 213). Calculation was facilitated by arranging the cards in order of increasing ranks of the first variable and recording the sequence of ranks of the second variable. A simple operation with the cards is substituted

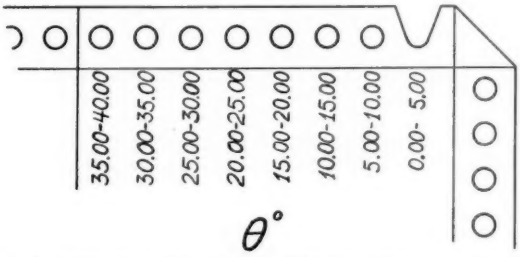

FIGURE 1.—SECTION OF PUNCHED CARD SHOWING θ FIELD AND CLASS LIMITS
This basin had its mean valley-side slope between 0.00° and 5.00°.

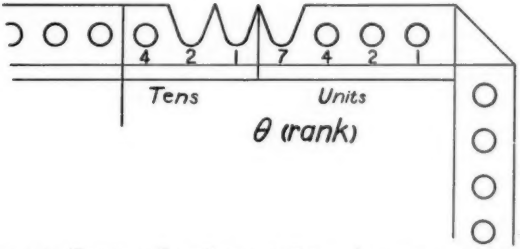

FIGURE 2.—PORTION OF A PUNCHED CARD SHOWING FIELD ALLOTTED TO θ, PUNCHED TO INDICATE A RANK OF 37

provides the simplest sorting procedure, and is easiest to prepare.

In a second study, information from 59 drainage basins on 15 characteristics, similar to the data used in the study described above, was recorded in another set of punched cards by using a 7 4 2 1 sequence code (Casey and Perry, p. 281). All the 105[1] possible two-variable correlation coefficients were computed—a lengthy task by conventional methods, but one which required only a few days in this case. The rank, from 1 to 59, of every basin of the sample in each of the 15 variables was found and recorded on its card (Fig. 2). It was then possible to arrange the cards rapidly in order of increasing sample value of any one of the variables.

The measure of correlation best suited for use with punched cards prepared in this way is probably Kendall's τ. The method of calculating τ for some two variables is explained by Siegel

[1] 105 = the combinations of 15 things taken two at a time.

for inspecting, rearranging, and copying of tabulated data. The 14 correlation coefficients involving the first variable were found after ordering the cards only once. When instead of ranks the actual sample values are recorded on the cards, the cards can still be ordered and τ calculated in the same manner. Thus, sets of cards not specifically prepared for rank correlations can be used for this purpose without alteration.

In addition to correlation analysis, certain other nonparametric analyses can be done more easily and quickly with punched cards than with tabulated data. Contingency tables for chi-square and other tests can be made in the same manner as the correlation tables mentioned above, and extension to three or more dimensions is possible. For comparing the central tendencies of two independent samples of the same characteristic or variable, the median test, Wald-Wolfowitz runs test, or the Moses test of extreme reactions (Siegel, 1956, p. 111, 136, 145), all substitute t tests, seem

particularly well suited. For each of these tests, the two samples are combined, ordered in the variable under consideration, and observations are made on the distribution of the members of the two samples. The combined median needed for the median test can be found simply by dividing the ordered set of cards into two equal parts and noting the value of the variable at that point in the sequence. As computations for these tests are fairly simple, they can be used with less tedium when a vast amount of data is involved, in which case punched cards can further simplify computations by eliminating much sorting by inspection, arranging, and recording of numbers.

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ROCK DENSITIES OF THE CENTRAL VENEZUELAN ANDES

BY J. HOSPERS AND J. C. VAN WIJNEN

Introduction and Acknowledgments

In order to reduce gravity measurements on land to yield Bouguer anomalies, it is necessary, among other requirements, to know the density of the land mass above sea level. In low-lying areas an approximate figure is usually all that is required, but in mountain areas, where station elevations may be high, the value employed is critical. It is customary to use a value of 2.67 g. cm^{-3}, but for gravity studies of an area of limited extent this figure is not necessarily the best one.

The authors have been engaged in the reduction of gravity measurements in the central Venezuelan Andes (Cordillera de Mérida) where the highest gravity stations are situated at about 4000 m altitude. To obtain an accurate knowledge of the density of the rocks in the area, the present study was made.

The authors wish to thank Dr. J. E. Smith, Exploration Manager (Western Division) of the Cía. Shell de Venezuela, for enabling them to obtain both the density and the gravity data in the central Venezuelan Andes. Their thanks are also due Mr. R. S. Schols of the Regional Production Laboratory (Cía. Shell de Venezuela) at Maracaibo, under whose supervision the density determinations were made.

Sampling

Fresh rock samples were taken from roadside exposures along the following roads (Fig. 1): (1) the road from Barinitas, via the Paramo de Mucuchies, and Timotes, to Valera; (2) the road from the Paramo de Mucuchies, via Mérida, and Egido, to Lagunillas; (3) the road from Egido, via La Azulita, to the Carretera Panamericana.

The average distance along the road between samples was 4 km, although individual distances ranged from 0.1 to 10 km. Large hand specimens were taken as samples.

Density Determinations

The density measurements were carried out by means of a specific-gravity balance, which weighs the specimen in air and in water. The density is read directly to within 0.01 g. cm^{-3}.

The samples used had an average volume of 10 cm^3 and were obtained by breaking the hand specimens and selecting a suitable fresh and representative fragment.

The porosity and the extent to which the pores are filled with fluid in the natural state was not investigated. It is not believed that this will affect the reliability of the density values found for the igneous and metamorphic rock samples (74 out of 96). The samples were fresh and had no macroscopically detectable porosity. Moreover, these rock types (granites, gneisses, schists, and some basic rocks) have very low porosities (less than 1 per cent).

The sedimentary rock samples consisted of 22 well-consolidated sandstones, dense limestones, and shales of Mesozoic and Tertiary age. Some of the sandstones showed macroscopically detectable porosity, and, even though only fresh samples were used, their measured density may be somewhat lower than the natural density.

Methods of Statistical Analysis Used

The samples were separated into various groups (Table 1). For each group the mean density value and the standard deviation were computed. The standard deviation is defined as the square root of the sum of the squares of the deviations of the observations from the (arithmetic) mean, divided by the square root of one less than the total number of observations.

To determine whether the difference between the mean density value of a group and a given fixed value (2.670) is significant, the standard error of the mean was computed by dividing the standard deviation by the square root of the number of samples in the group. The probability that the difference between the mean and the fixed value will exceed twice the standard error of the mean by chance is only about .05, or 5 per cent. Hence, if the difference is larger than twice the standard error of the mean, the difference is significant; if smaller it is not significant.

This statement is true only for large samples,

such as groups 1 and 2 in Table 1. For small samples use has to be made of the t Distribution (Fisher, 1950, Chapter V; Dixon and Massey, 1951, p. 97). For the purpose of this paper it is sufficient to note that for the same with n, the number of degrees of freedom. In the present analysis n is always 2 less than the sum of all observations in the two groups which are being compared. In Fisher's Table of t can be found the accompanying value of P, the

TABLE 1.—STATISTICAL ANALYSIS OF ROCK DENSITIES

Group No.	Description	Number of samples	Mean density	Standard deviation	Standard error of mean	Difference of mean with 2.670	Difference of means
1	All samples	96	2.650	0.107	0.011	Not significant	
2	Igneous and metamorphic rocks	74	2.685	0.075	0.009	Not significant	Significant: $t = 7.2$, $n = 94$, $P < .01$
3	Nonmetamorphic sediments	22	2.531	0.121	0.026	Significant	
4	Granites	26	2.639	0.028	0.006	Significant	For groups 4 and 5: $t = 3.7$, $n = 41$, $P < .01$
5	Gneisses	17	2.694	0.069	0.017	Not significant	Significant
							For groups 4 and 6: $t = 4.4$, $n = 44$, $P < .01$
6	Schists	20	2.703	0.068	0.015	Significant	Significant
							For groups 5 and 6: $t = 0.40$, $n = 35$, $P = .7$
7	Rest*	11	2.748	0.090	0.027	Significant	Not significant
8	0–2000 m altitude†	42	2.683	0.067	..	..	Not significant: $t = 0.55$, $n = 72$, $P = .6$
9	2000–4000 m altitude†	32	2.692	0.077	..	..	

* Rest of igneous and metamorphic rocks.

† Igneous and metamorphic rocks only.

level of significance (.05, or 5 per cent), the decisive ratio of difference and computed standard error of the mean is slightly higher than 2.0. For groups 3–6 in Table 1 the difference between the mean and 2.670 is significant if the difference is more than 2.1 times the standard error of the mean, for group 7 if the difference is more than 2.2 times the standard error of the mean.

In some instances it is desirable to test the significance of the differences among mean density values of different groups. This analysis again rests on the t Distribution. The quantity t is found by dividing the observed difference of the means by its estimated standard error. The error of the estimation is allowed for by entering the Table of t (Fisher, 1950, p. 174) probability that the computed value of t is exceeded by chance. In Table 1 the appropriate values of t, n, and P are shown for each comparison of mean values made. Since the total number of samples involved in each comparison made between means in Table 1 is large, the difference is significant (on a 5 per cent level) if t exceeds 2.0, and not significant if t is less than 2.0.

The above methods may be legitimately applied to "cases in which we have not sufficient evidence to assert that the original distribution was normal, but in which we have reason to think that it does not belong to the exceptional class of distributions for which the distribution of the mean does not tend to normality" (Fisher, 1950, p. 114).

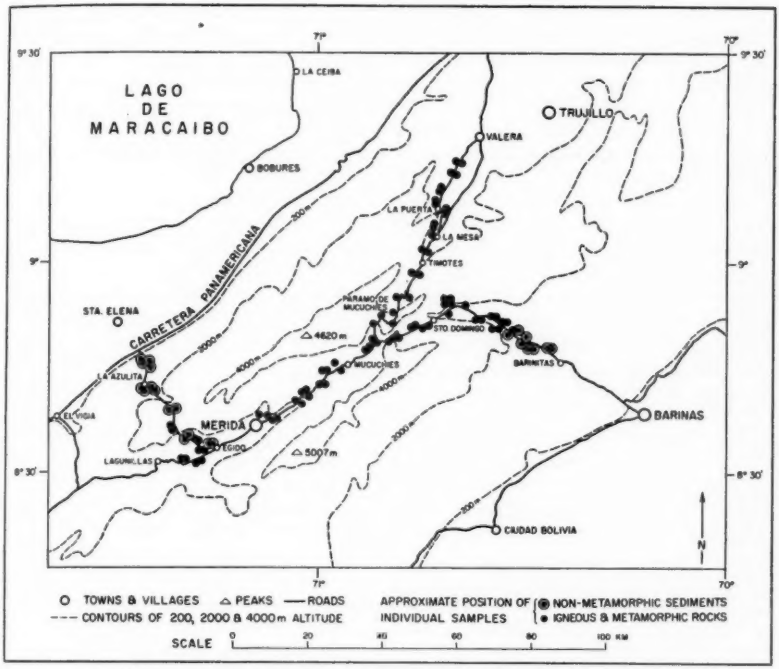

FIGURE 1.—SKETCH MAP OF THE CENTRAL VENEZUELAN ANDES
Showing locations where rock samples were taken

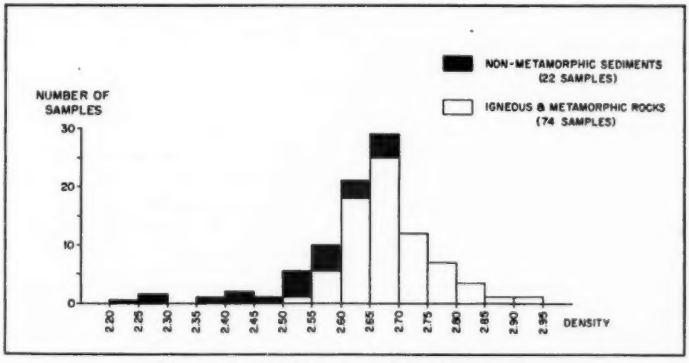

FIGURE 2.—HISTOGRAM OF ROCK DENSITIES

Results of Statistical Analysis of Rock Densities

Table 1 shows the results of the statistical analysis of all density measurements and of the groups into which they can be divided.

The mean density of group 1 (all samples) is 2.650; this value is just still reconcilable with a true average density of 2.670. In order to arrive at a satisfactory density figure for the Venezuelan Andes, however, it is better to distinguish between nonmetamorphic sediments and igneous and metamorphic rocks. This distinction has been made in Figure 1, from which it will be noted that samples of nonmetamorphic rocks were taken northwest of Barinitas and around La Azulita. Inspection of a geological

map of the area will show that, considering their areal extent alone, the non-metamorphic sediments are under-represented in the total sample (22 out of 96). In spite of their large areal extent on the geological map, however, their contribution to the total volume of rock above sea level is small because they form only relatively thin veneers.

The relative volumes of nonmetamorphic sediments and other rocks have been estimated from the cross-sectional areas of each on three cross sections of the Venezuelan Andes, prepared by our colleague Dr. K. Habicht. The first section runs across the Andes near Barinas and Valera, the second near Mérida, and the third well off the southwest corner of our map near La Grita. From these sections the volume of the nonmetamorphic sediments is estimated to be about 10 per cent of the total volume of the central Venezuelan Andes. The mean densities for nonmetamorphic sediments and the rest (igneous and metamorphic rocks) therefore should be combined in a corresponding proportion to obtain a correct overall density.

The required mean densities are shown as those of groups 2 and 3 in Table 1. These two groups differ significantly in their means, indicating that we are dealing with two different populations of density values. This is also illustrated by Figure 2. The igneous and metamorphic rock densities approach a normal distribution.

Combining the mean densities of groups 2 and 3 of Table 1 in the correct volumetric proportion, it is found:

$$\text{average density} = .9 \times 2.685 + .1 \times 2.531$$

$$= 2.670 \text{ g.cm}^{-3}.$$

Surprisingly, this agrees exactly with the commonly used figure. The above figure, however, is a lower limit, owing to the fact that the mean density of the nonmetamorphic sediments may be somewhat too low. The above average density would be 2.680 if the average sediment density were 2.635. This seems somewhat too high, and 2.670 is therefore considered as the best figure.

An average density of 2.670 g.cm^{-3} is a reliable figure for topographical corrections and isostatic corrections in gravity work. However, for high-altitude stations situated exclusively on igneous and metamorphic rocks the effect of the veneers of nonmetamorphic sediment is practically nil. For the Bouguer correction of these stations it might therefore seem better to use the mean density of the igneous and metamorphic rocks (group 2 in Table 1). This mean density is 2.685. As, however, this mean value is not significantly different from 2.670 there is no justification for using a figure different from 2.670. Here too, 2.670 is therefore indicated as the best figure.

In any case, for a station at 4000 m altitude, an error of 0.01 in the density causes an error of only 1.7 mgal in the Bouguer correction. Given the magnitude of other sources of error in gravity work in mountain areas, this error is small enough to be disregarded.

Mean densities for granites, gneisses, and schists are also shown in Table 1. The mean density of the gneisses is the only one not significantly different from 2.670, and the gneisses (and not the granites) are therefore closest to being the average rock in respect of density. The granites are significantly lighter than either gneisses or schists. This is in agreement with the usual interpretation of negative gravity anomalies over granite bodies which ascribes the negative anomaly to the density contrast between the lighter granite and the heavier metamorphic rocks surrounding it.

Finally, the igneous and metamorphic rocks have been separated into two groups according to their altitude (groups 8 and 9 in Table 1). Table 1 shows that the difference between the means is not significant, and hence that there is no evidence here of a relation between density and altitude of the samples.

Conclusions

The average density found for the central Venezuelan Andes is 2.670 g.cm^{-3}. This constitutes a reliable figure for all corrections necessary in gravity work in the central Venezuelan Andes into which the density enters.

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